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An application of encounter rate modelling to vessel traffic in Puget Sound.

Adams, Bruce Charles.

AN APPLICATION OF ENCOUNTER RATE MODELLING TO VESSEL TRAFFIC IN PUGET SOUND

BRUCE CHARLES ADAMS

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AN APPLICATION OF ENCOUNTER RATE MODELLING TO VESSEL TRAFFIC IN PUGET SOUND

by

BRUCE CHARLES ADAMS

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Master's Thesis

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INTRODUCTION

World-wide concern has been expressed over the increasing trend in vessel casualties, and their consequential effects to both loss of life and environmental damage. Attempts to identify the inherent risks involved in the water-borne transportation system have resulted in analysis of vessel casualty history, and projections of the rate of occurrence and impact of future casualties based on predictions of shipping growth. This study will develop a model of vessel encounter rates, using concepts derived from previous studies of vessel encounters. This model will be applied to data on vessel movements within the Puget Sound region in an attempt to identify those areas having a high rate of vessel encounters, and consequently a high rate of vessel collision. It is hoped that the incorporation of the concepts of an encounter rate model may provide some means to identify the impact of the changing characteristics of vessel traffic, as well as to measure the effects of continuing efforts to improve and enhance the existing vessel traffic management system.

Chapter 1

PUGET SOUND VESSEL TRAFFIC SYSTEM

VESSEL TRAFFIC SYSTEM DEVELOPMENT

The Ports and Waterways Safety Act of 1972 (PL 92-340) authorizes the Secretary of the Department of Transportation to "establish, operate, and maintain vessel traffic services and systems for ports, harbors, and other waters subject to congested vessel traffic. . . ." In September of 1972, the Secretary of the Department of Transportation delegated this authority to the Commandant of the Coast Guard. The purpose of the vessel traffic system (VTS) program is to:

> . . . prevent damage to, or the destruction or loss of any vessel, bridge, or other structure on or in the navigable waters of the U.S., or any land structure or shore area immediately adjacent to those waters; and to protect the navigable waters and the resources therein from environmental harm resulting from vessel or structure damage, destruction, or loss. . . .[1]

In undertaking this task, the Coast Guard began a concentrated effort to identify the mechanism of collision avoidance and the underlying causes of marine accidents. The VTS program was based in part upon the following premises:

1. Commercial vessel traffic in the ports and waterways of the United States will increase substantially in the next ten years. The number of commercial vessel transits through all potential VTS zones in the United States was estimated at 3.1 million in 1960, 3.9 million in 1970, and projected to be 4.5 million by 1977.[2]

2. The potential for a major incident resulting in loss of life, personal injury, loss of economic goods and services, and ecological damage will substantially increase unless more effective preventative measures are implemented. The amount of hazardous and potentially polluting cargo transported on United States waterways increased from 659 million tons in 1960 to 980 million tons in 1970, and is estimated to increase to almost 1,500 million tons in 1977.[3] Furthermore, the accident frequency per billion of ton-miles for vessels transporting hazardous cargo was increasing at an average rate of 20.5 percent for the period from 1957 to 1968.[4]

3. Collisions, rammings, and groundings in United States ports and waterways are causing deaths, injuries, and loss of or damage to vessels and cargo, and damage to the environment at an unacceptable rate.[5]

The objective of vessel traffic systems, as defined by the Coast Guard, is to reduce the probability of vessel collisions, rammings, and groundings while facilitating the orderly movement of vessels through or within the navigable waters. In a VTS, a Vessel Traffic Center will function as an arbiter by making a decision when one or more users wants to utilize a given portion of a waterway at the same time. In order to accomplish its objective, the VTS must impose certain operational and equipment requirements on all users, and require adherence to certain rules and regulations designed to minimize the probability of accidents.

VESSEL TRAFFIC SYSTEM ELEMENTS

The United States Coast Guard Study Report "Vessel Traffic Systems Issue Study" described the practical means of achieving the short and long term program goals of reducing collisions, rammings, and groundings. The result of the Study was the definition of a workable number of finite components, referred to as elements, that form the building blocks of a VTS. These elements, ranging from simple to very sophisticated in terms of operational hardware, can be combined to form sub-systems of the total VTS which are designed to best satisfy the needs of a specific geographical sector of a port or waterway. The sub-systems can then be integrated into a total system based upon the degree of traffic management necessary, and the extent of participation desired.

The basic elements of a VTS are:

1. Traffic Separation Scheme (TSS). The TSS has passive management capability, and provides guidance to the vessel master by aids to navigation, traffic lanes, and traffic routing schemes.

2. Vessel Movement Reporting System (VMRS). The VMRS has advisory management capabilities. Vessels will report their position and intended movements and other pertinent data to the Vessel Traffic Center (VTC) where it will be recorded and made available to other participants. Participation will be mandatory for certain classes of vessels, and vessels not included in this category may participate on a voluntary basis.

3. Basic Surveillance. The addition of basic radar or other basic electronic surveillance equipment provides the VTS with limited capabilities to exercise active management. Advisory management will normally be used to relay information received from vessels or interested participants. The system will use active management techniques when a dangerous situation appears to be developing. The VTC may then control channel movements, routing of dangerous cargo, or other situations.

4. Advanced, or Automated Advanced Surveillance. These elements consists of a combination of a more complex radar system, T.V. monitoring system, or other advanced electronic surveillance equipment, which will enable the VTC to more accurately fix a vessel's position and actively manage vessel movements. Management may be initially advisory, shifting to active management when a dangerous situation appears to be developing. An automated system will increase the capability for rapid position fixing, vessel identification, and more accurate traffic management. The system implies active management, and can handle a larger number of vessels under mandatory participation, and also allows reduced manning as a tradeoff for higher initial costs.

The various VTS elements can be combined to form a system or sub-system to determine the level of sophistication and type of management for the total system. For example, the port of San Francisco, which was the first United States prototype for the VTS, has been divided into four sub-systems

based on geography. Two of the four areas have a traffic separation scheme and three are covered by a vessel movement reporting system. Furthermore, the heavily trafficked inner harbor area is covered by an advanced automated surveillance active management system.[6] Both the San Francisco Bay and Puget Sound Vessel Traffic Systems were established as pilot programs for a national system of vessel traffic management. Experience gained from these two projects served as a standard by which to evaluate further system development.

The decision to establish the Puget Sound VTS was based on an anticipated increase in petroleum shipments, and public pressure to protect the pristine quality of the Puget Sound environment from contamination due to potentially higher risks of vessel collision. An unpublished traffic survey conducted during June 1973 showed that tanker traffic made up four percent of the total vessel traffic which entered into the VTS during the previous year. This traffic survey was an initial step taken to determine areas of high traffic density, and therefore higher risk of collision potential. The results of this preliminary survey were to serve as siting criteria for radar installations to augment and improve the existing radio reporting and manual plotting traffic control system.

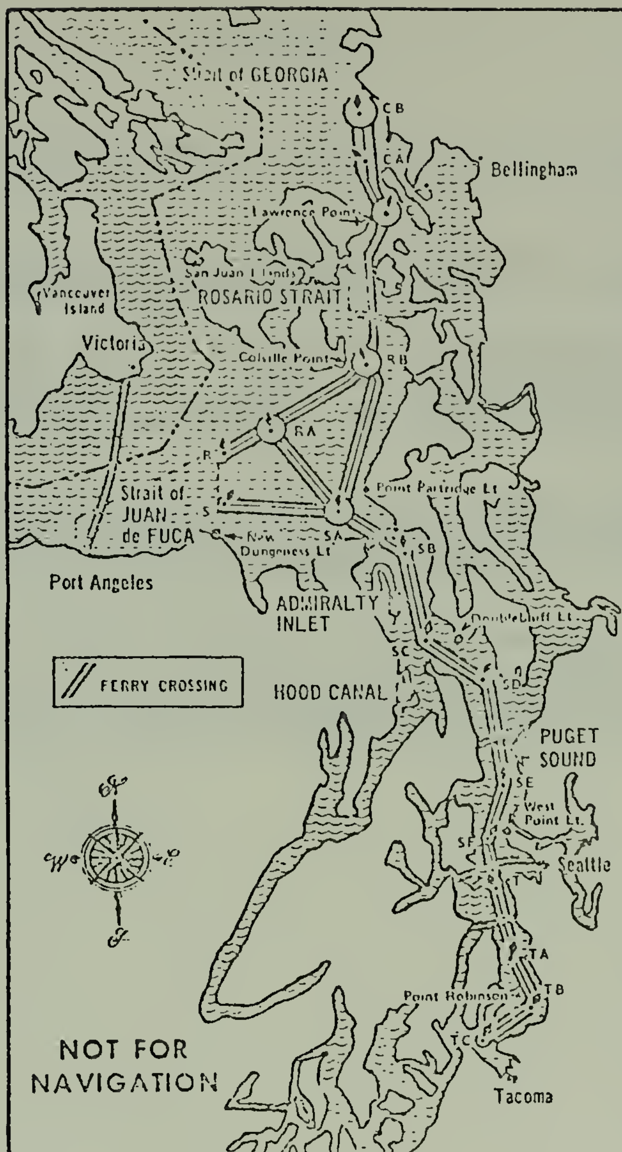

Figure 1-1

Puget Sound Vessel Traffic System. Traffic lanes and ferry crossings. (Source: Department of Transportation, Puget Sound Vessel Traffic System.)

FOOTNOTES

[1]Ports and Waterways Safety Act of 1972 (PL 92-340), Title I, Section 101.

[2]"Naval Maritime and Military Forces," U.S. Naval Institute Proceedings, Naval Review, May 1972, pp. 332-333.

[3]U.S. Army Corps of Engineers, Waterborne Commerce of the United States, Part 5, 1970. and Feasibility of a North Atlantic Deepwater Oil Terminal, Maritime Administration, July 1972.

[4]National Transportation Safety Board, Analysis of the Safety of the Transportation of Hazardous Materials on the Navigable Waters of the U.S., March 1972.

[5]T. V. Johnson, "Conceptual and Practical Framework for VTS," Proceedings of the National Security Industrial Association Symposium on Coast Guard Vessel Traffic Systems, May 1973, U.S. Coast Guard, Washington, D.C., pp. 102-105.

[6]Ibid., p. 112.

Chapter 2

CHARACTERISTICS OF VESSEL TRAFFIC WITHIN PUGET SOUND

Introduction

The development and application of an encounter rate model to traffic within the Puget Sound area required some knowledge of the general patterns and characteristics of vessel traffic. A Traffic Density Survey conducted by the United States Coast Guard Puget Sound Vessel Traffic System provided information on the origin and destination of vessel traffic during June of 1973. Further information was extracted from the records maintained by the Puget Sound VTS in an attempt to identify various characteristics of vessel traffic, in order to provide a typical traffic profile for use in modelling vessel encounter rates. The traffic characteristics identified were the various classes of vessels, average length within a class of vessels, average transit speed for a class of vessels, and peak hours of traffic density.

IDENTIFICATION OF CHARACTERISTICS

An attempt to identify various characteristics of the traffic within the Puget Sound region was made utilizing data extracted from the records of the United States Coast Guard Puget Sound Vessel Traffic System. The goal of this survey was to determine the following traffic characteristics:

1. Identification of the number of vessels of various classes utilizing the VTS. These classes were broken down into general categories such as tankers, freighters, towing boats, and miscellaneous vessels.

Tankers are defined as self-propelled vessels normally engaged in (or designed for) the transport of petroleum products in bulk.

The classification of freighters consist of all self-propelled vessels engaged in carrying (or designed to carry) dry (or liquid other than petroleum) bulk cargo or general cargo. This includes commodities such as ore, grain, lumber, containers, automobiles, etc.

Towing boats are defined as vessels designed for, or engaged in the pushing or towing of barges, rafts, or other vessels.

Miscellaneous vessels include all other vessels which have entered into the Puget Sound VTS. These include all Washington State Ferries which were not on scheduled runs, and all passenger ferries engaged in interstate or international commerce, such as Alaska and Canadian bound vessels. The miscellaneous class of vessels further includes all military vessels, oceanographic research vessels, and any other type of vessel which does not fit into the category of tanker, freighter, or towing boat, and is entered in the Vessel Traffic System.

2. Determination of the characteristic length of vessels within each class of vessels. The length of all

vessels between perpendiculars, and length-over-all was utilized to determine the mean length of vessels within each class. Attempts were made to determine if the characteristic lengths of several different classes of vessels could be represented by one length. This involved tests to determine if the differences between the mean lengths were statistically significant.

3. Determination of the average speed utilized by each class of vessel while transitting the Puget Sound region. Speed of advance was derived from a card maintained on each vessel as it makes a transit within the Puget Sound VTS. Information contained on the card included the approximate time and area or point at which a vessel entered the system, its ultimate destination, and the point at which a vessel was checked out of the system. During the transit, vessels are required to check in at various locations (i.e. specific buoys), and the location and time is noted. Vessels indicate their estimated Speed of Advance at initial check-in.

From this information, average transit speed was determined by class of vessel. The vessel's own estimate of Speed of Advance was utilized for this calculation, and compared to the estimated actual speed by computing the time between two check-in points of known distance.

Attempts were made to determine if the average speed of several classes could be represented by one speed, in the same manner as characteristic length.

4. Determination of peak hours of traffic density. An attempt was made to identify the hours of the day, and days of the week when traffic density significantly differed from the average density. Here density will be defined as the number of vessels transiting within the VTS during any given hour.

This data was recorded by class of vessel, over three one-week periods. The one-week periods were selected from an analysis of monthly and daily traffic volume. The weeks were selected on the basis of a high and mean average traffic volume.

MONTHLY TRAFFIC DENSITY

An analysis of traffic density and a determination of traffic density patterns was made, utilizing data obtained from the records of the Puget Sound VTS. Those records utilized for this study consisted of the traffic volume statistics for the period of June 1973 to May 1974.

A profile of the monthly traffic totals for this period appears in Table 2-1. The monthly totals are divided into classes of towing boats, freighters, tankers, and miscellaneous vessels. The monthly totals consist of the sum of the vessel transits occurring during each month.

The data of Table 2-1 was averaged to find the average daily traffic, by types, for each month. From this information it was determined that the average day of the one-year period under study contained the following traffic profile:

Table 2-1

Monthly Traffic Volume
Puget Sound Vessel Traffic System
(Percent of Monthly Total)

Vessel Class	June 1973	July	August	September	October	November
Freighters	360 (17.2)	345 (16.5)	360 (15.9)	314 (15.3)	346 (16.7)	351 (18.6)
Tankers	62 (3.0)	71 (3.4)	76 (3.4)	67 (3.3)	76 (3.7)	95 (5.0)
Tow Boats	1369 (65.4)	1315 (62.8)	1502 (66.5)	1405 (68.5)	1393 (67.0)	1255 (66.4)
Miscellaneous Vessels	301 (14.4)	361 (17.3)	322 (14.2)	264 (12.9)	262 (12.6)	187 (9.9)
Total	2092	2092	2260	2050	2077	1888
Average Daily Transits	69.7	67.5	72.9	68.3	67.0	62.9

Table 2-1 (Continued)

Vessel Class	December 1973	January 1974	February	March	April	May
Freighters	322 (17.3)	299 (15.0)	278 (15.0)	325 (17.4)	350 (16.0)	329 (15.2)
Tankers	77 (4.0)	81 (4.0)	56 (3.0)	87 (4.6)	83 (3.8)	69 (3.2)
Tow Boats	1318 (68.6)	1363 (68.5)	1263 (68.4)	1282 (68.5)	1519 (69.6)	1493 (69.2)
Miscellaneous Vessels	195 (10.1)	246 (12.4)	250 (13.5)	178 (9.5)	231 (10.6)	267 (12.4)
Total	1922	1989	1847	1872	2183	2158
Average Daily Transits	62.0	64.1	66.0	60.4	72.7	69.6

Source: Traffic Totals 1973 and 1974, United States Coast Guard Puget Sound Vessel Traffic System, Seattle, Washington.

Average Tow Boat transits:	45.2 $\pm$ 2.9
Average Tanker transits:	2.5 $\pm$ 0.3
Average Freighter transits:	10.9 $\pm$ 0.7
Average Miscellaneous transits:	8.4 $\pm$ 1.8
Average Total transits:	66.9 $\pm$ 4.0

DAILY RANGE OF TRAFFIC VOLUME

Over the entire length of the period under observation, daily vessel traffic ranged from a low of 11 vessel transits per day on December 25, 1973, to a high of 100 vessel transits per day on April 18, 1974.

The frequency distribution for vessel transits per day is represented in Table 2-2. The mean was found to be 64.6 vessel transits per day, and the standard deviation was 12.6.

A graphical presentation of the cumulative frequency of occurrence of vessel transits is represented by Figure 2-1. This may be interpreted to mean that on approximately 47 percent of the days during this year, there occurred less than 64.64 transits per day. On 50 percent of the days the traffic volume exceeded approximately 66 vessels transits per day. On 15 percent of the days of the year, daily traffic volume exceeded 78 vessel transits per day.

WEEKLY RANGE OF TRAFFIC VOLUME

Over the length of the period under observation, weekly traffic volume ranged from a low of 301 vessel transits per week, (during the period from December 30, 1973 to

Table 2-2

Daily Range of Traffic Volume (Puget Sound Vessel Traffic System June 1, 1973 to May 31, 1974)

Vessel Transits Per Day	Frequency Of Occurrence	Cumulative Frequency
10- 19	1	1
20- 29	1	2
30- 39	7	9
40- 49	16	25
50- 59	69	94
60- 69	109	203
70- 79	99	302
80- 89	56	358
90- 99	6	364
100-109	1	365

Mean Vessel Transits Per Day: 64.6

Standard Deviation: 12.6

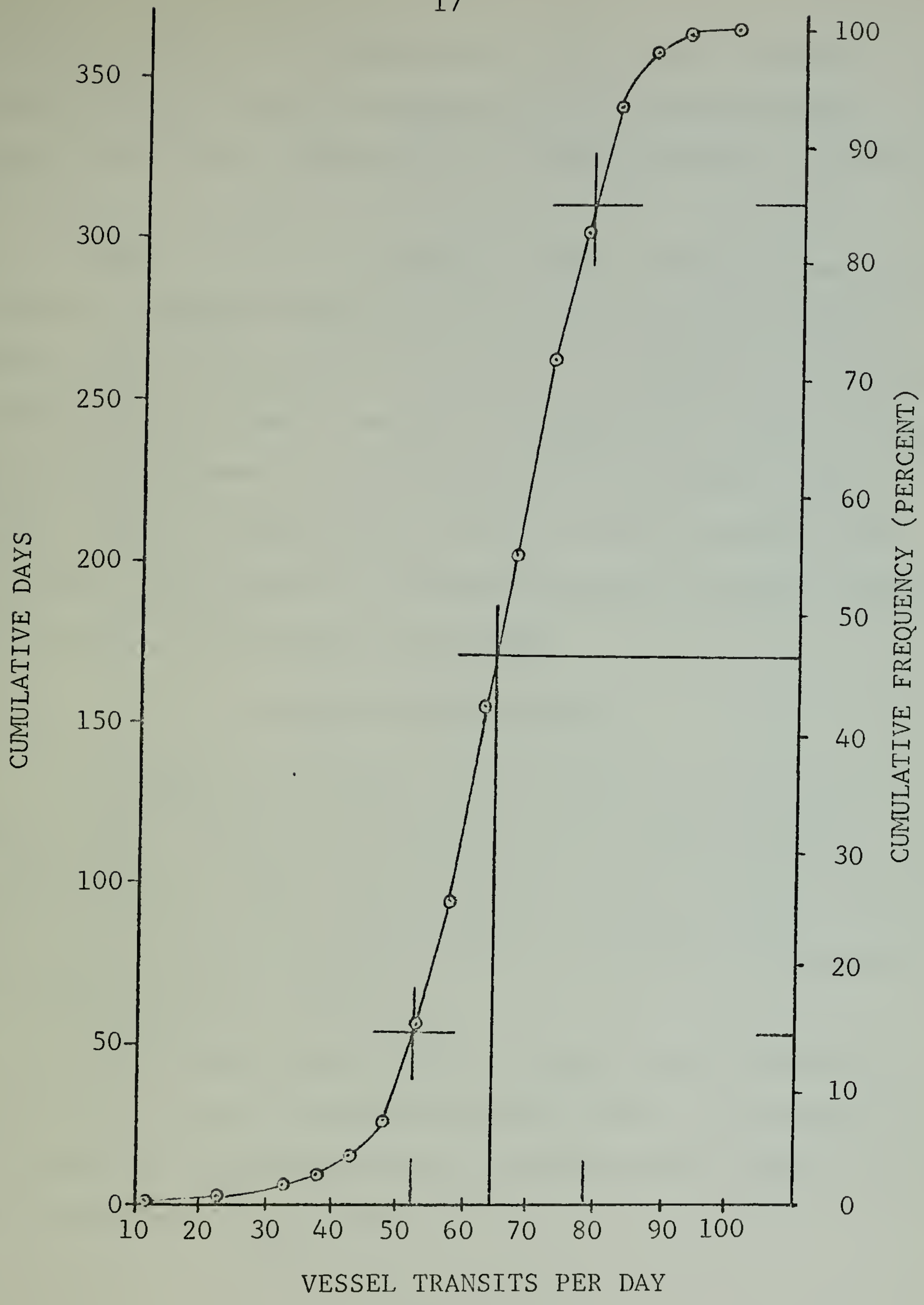

Figure 2-1

Cumulative Frequency Distribution
Of Daily Vessel Transits

January 5, 1974), to a high volume of 566 vessel transits (during the week of 21 to 27 April 1974). The mean number of vessel transits per week was 469.9, with a standard deviation of 46.2.

Table 2-3 lists the weekly traffic volume by seven day (Sunday to Saturday) period for the year under investigation. Figure 2-2 is the Cumulative Frequency Distribution for weekly traffic volume. From an analysis of Figure 2-2, traffic volume higher than the mean volume occurred on 38 percent of the weeks. Traffic volume greater than 516 vessel transits per week (mean volume plus one standard deviation) occurred during five percent of the weeks of the year.

HOURLY TRAFFIC DENSITY

Two weeks of the year were selected for an analysis of hourly traffic volume, and variations in traffic density. This two week traffic volume study was also correlated with a third week, in an attempt to identify times of the week during which peak traffic density occurs.

The average weekly traffic volume of the three week period is 507 vessel transits per week, which is representative of a seven day period during which higher weekly traffic occurs only ten percent of the year.

Table 2-3

Weekly Range of Traffic Volume (Puget Sound Vessel Traffic System June 1, 1973 to May 31, 1974)

Vessel Transits Per Day	Frequency Of Occurrence	Cumulative Frequency
300-319	1	1
320-339	0	1
340-359	1	2
360-379	0	2
380-399	1	3
400-419	2	5
420-439	6	11
440-459	6	17
460-479	13	30
480-499	9	39
500-519	11	50
520-539	2	52
540-559	0	52
560-579	1	53

Mean Vessel Transits Per Week: 469.9

Standard Deviation: 46.2

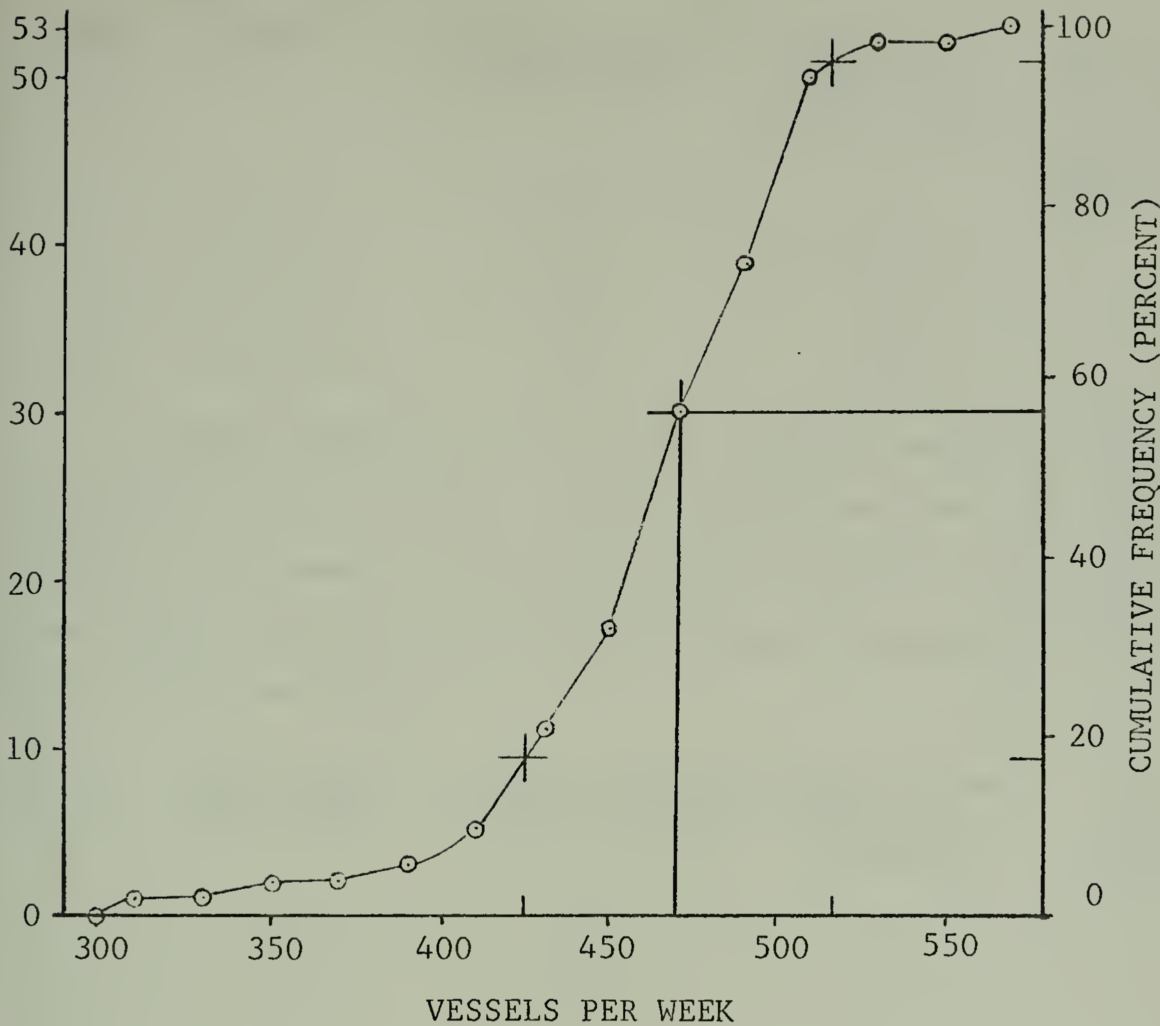

Figure 2-2

Cumulative Frequency Distribution
of Weekly Vessel Transits
For a One Year Period

The weeks selected for the study were:

Week	Date	Vessel Transits During Week	Percent of Weeks w/ Higher Volume	Deviation from the Mean (Standard Deviation)
I	7-13 Oct 73	474	30%	+ .11
II	14-20 Apr 74	518	4%	+ 1.04
III	9-15 Sept 73	530	2%	+ 1.30

During each hour of the week, a count was made of the number and type of vessels which were underway and utilizing the VTS. The measure of traffic density is then vessel-transit hours, which denotes the vessels underway during any portion of the 24 hours of the day.

Week	Vessel Transits Per Week	Vessel Transit Hours Per Week	Average Vessel Transits Per Hour	Hours Per Vessel Transit
I	474	2,466	14.7	5.2
II	518	2,747	16.4	5.3
III	530	2,899	17.3	5.57
Average	507	2,704	16.1	5.33

Based on hourly traffic density trends, as determined from the three week average, general trends or variations in weekly traffic volume exist. These trends show lower density during daytime periods than at night, and fewer vessel transit hours on Sunday, Monday, and Tuesday than on the remainder of the week. The 48 hour period from 1200 Wednesday to 1200 Friday appears to be a very heavily utilized period for waterborne traffic.

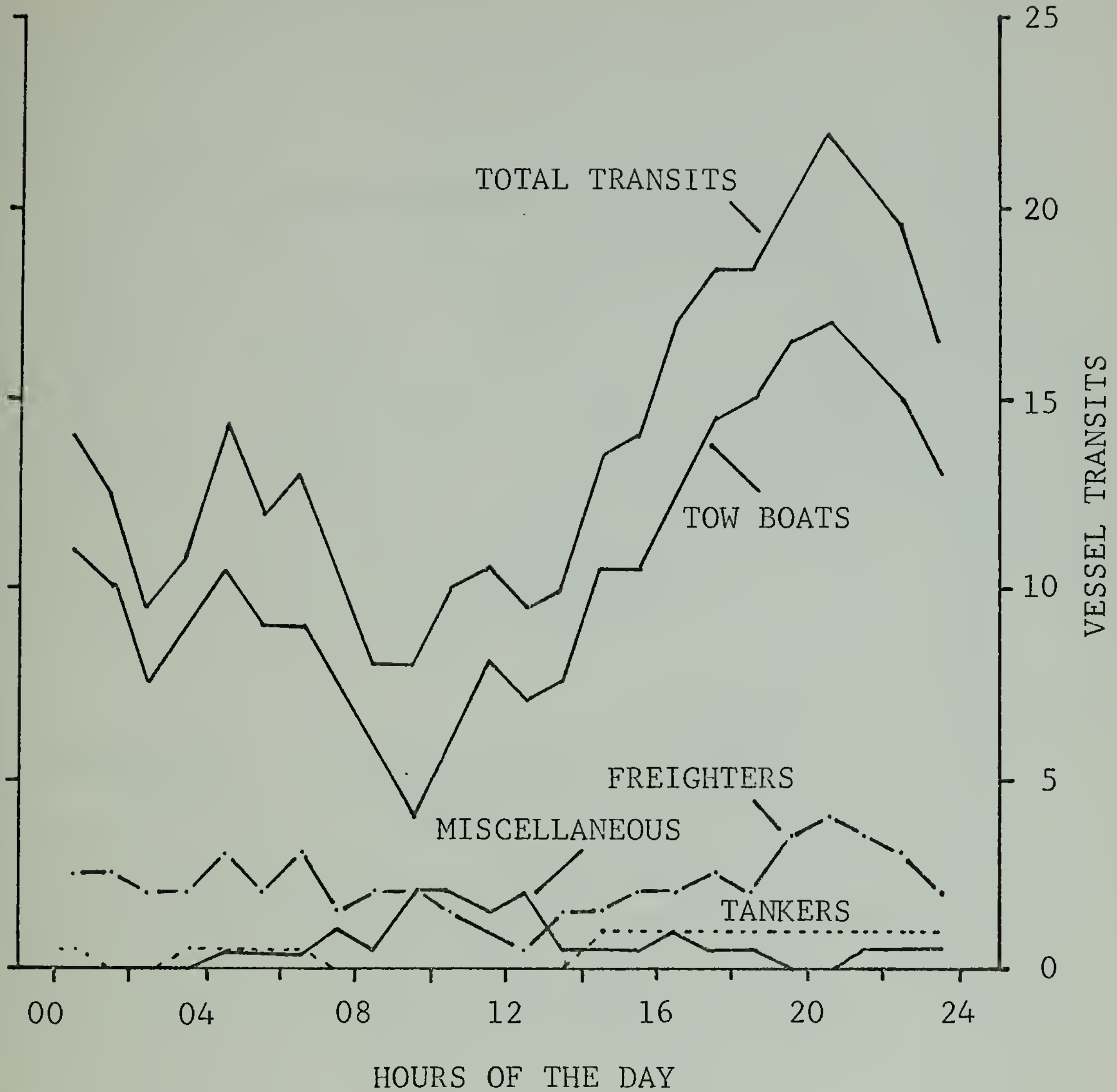

Figure 2-3

Hourly Variation in Vessel Transits
Two Week Average for Monday of the
Number and Class of Vessels
Participating in the VTS
During any Portion of
An Hour

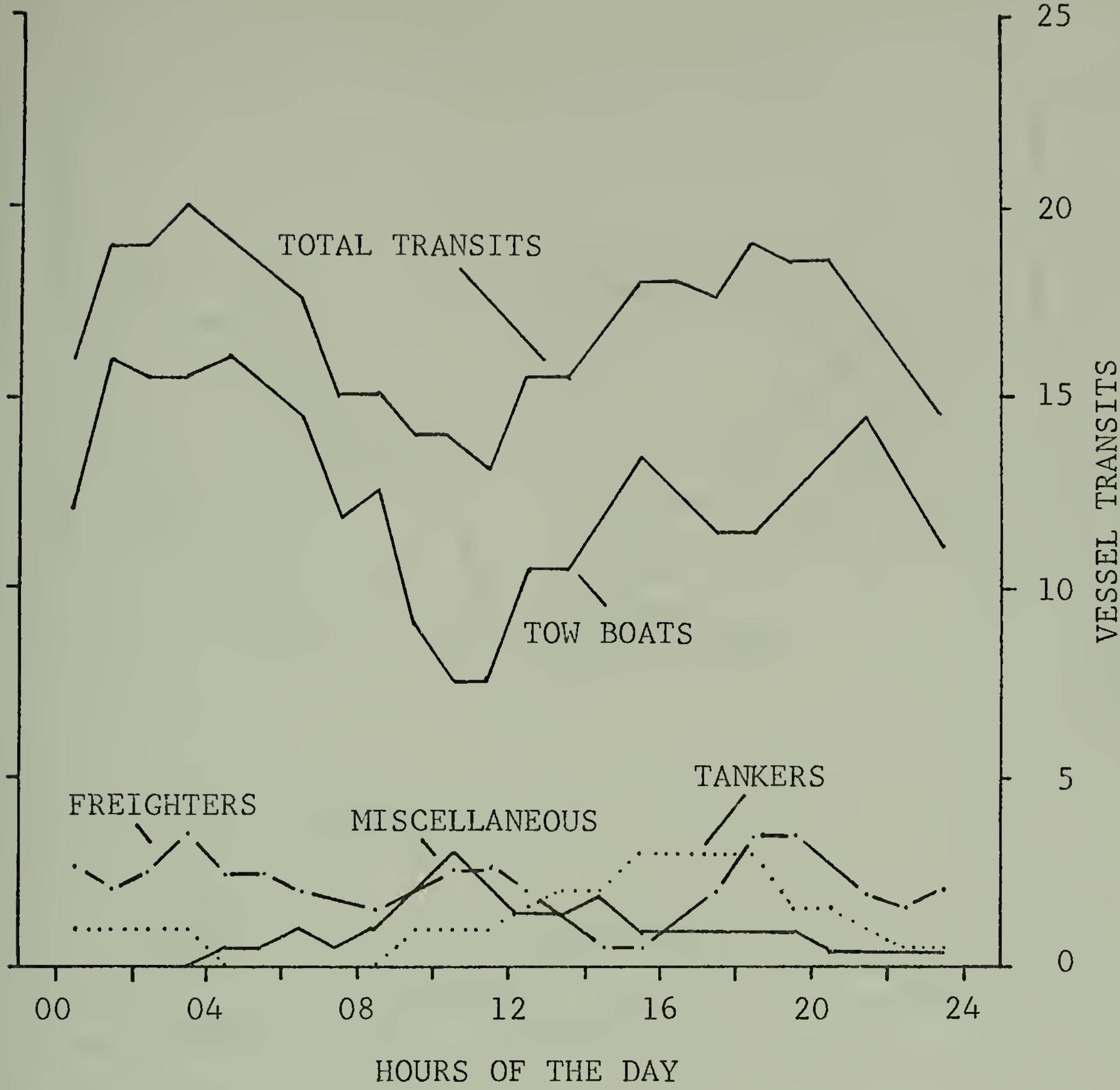

Figure 2-4

Hourly Variation in Vessel Transits
Two Week Average for Wednesday of
the Number and Class of Vessels
Participating in the VTS During
Any Portion of an Hour

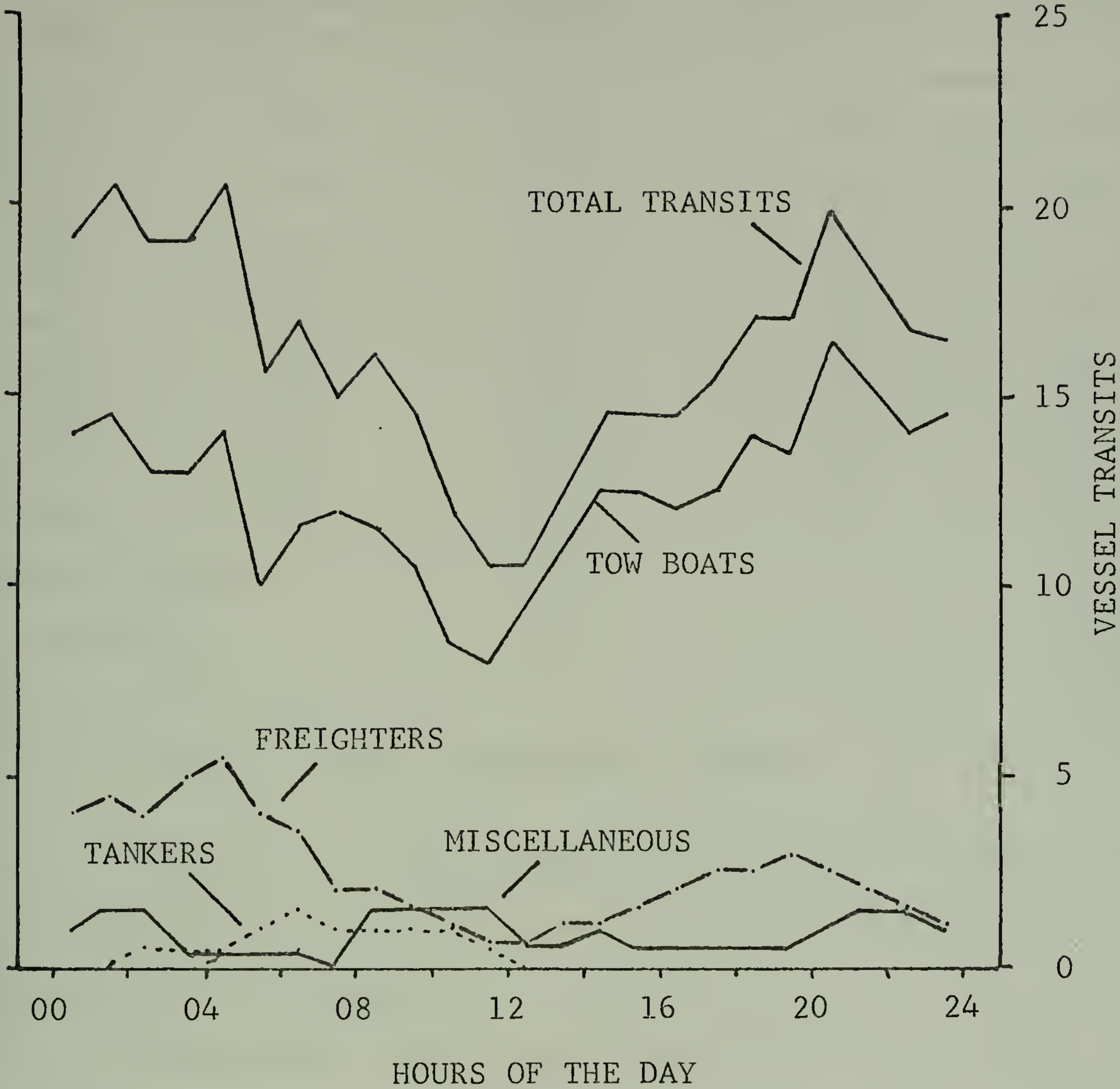

Figure 2-5

Hourly Variation in Vessel Transits
Two Week Average for Friday of the
Number and Class of Vessels
Participating in the VTS
During Any Portion
of an Hour

Day	Week I Total Vessel Hours	Week I Average (Per Hour)	Week II Total Vessel Hours	Week II Average (Per Hour)
Sun	296	12.3	326	13.6
Mon	323	13.5	339	14.1
Tues	323	13.5	369	15.4
Wed	402	[x]16.8	407	[x]17.0
Thurs	408	[x]17.0	456	[x]19.0
Fri	372	[x]15.5	409	[x]17.0
Sat	342	14.3	441	[x]18.4
Weekly Average Per Hour		14.7		16.35

[x]Denotes higher than weekly average.

The hourly trends evident from the three week average of traffic density illustrate major utilization of the VTS during hours of darkness.

Peak traffic hours, arbitrarily selected as being those hours during which 17 or more vessels were underway, were identified. Periods were limited to those in which three out of four consecutive hours had 17 or more vessel transits. Those peak hours (greater than 17 vessels per hour) are:

Day of Week	Hours	Cumulative Hours
Sun	00-02 19-23	6
Mon	16-24	14
Tues	00-06 18-24	26
Wed	00-06 12-24	44
Thurs	00-12 18-24	62
Fri	00-07 20-24	73
Sat	00-04 08-12 20-24	85

This 85 hour period represents 51 percent of the hours of the week. During this 85 hour period 58 percent of the vessel transit hours occurred. The average vessel transits per hour is 18.6. During the remainder of the week, (83 hours or 49 percent), 42 percent of the weekly vessel transit hours occurred. The average vessel transits per hour during this period of lower density is 13.6 vessels per hour.

When utilizing 18 vessels per hour to identify times of high traffic density, the peak hours of the week were determined to be as shown on the following page.

This 50 hour period represents 30 percent of the week, and 37 percent of the weekly vessel transit hours occur during this period. The average hourly volume during this period of high density is 19.8 vessel transits per hour. During the remaining 118 hours of the week (70 percent of the hours) the

remaining 63 percent of the traffic volume occurs. The average density of vessel transits per hour is 14.6 during these periods of lower vessel density.

Day of Week	Hours	Cumulative
Sun	None	
Mon	18-24	6
Tues	00-03 19-22	12
Wed	00-05 15-24	26
Thurs	00-06 19-24	37
Fri	00-05 20-24	46
Sat	00-04	50

VESSEL LENGTH

Tankers

From information extracted from the records of the two-week periods, a total of 38 transits were made by nine tankers. The vessels ranged in size from the ALMIZAR, 882' overall, at 108,620 DWT, to the Suamico, 524' overall, at 17,200 DWT. Averages for the two-week period were:[1]

Length overall (LOA)	609 ft.
Standard deviation	111 ft.
Length between perpendiculars (LBP)	584 ft.
Standard deviation	106 ft.
Deadweight tonnage (Summer load time)	30,200 DWT
Standard deviation	25,500 DWT

Freighters

During the period of 14-20 April 1974 there were 92 transits within the Puget Sound region by 61 freighters. Of these 61 vessels, sufficient information on three vessels could not be found to compute average size. The average freighter size, as determined from statistics available in *Lloyd's Register of Shipping* or from information obtained from the vessel owners' agents, has been determined for 58 vessels which made 88 transits of Puget Sound.[2]

Length overall (LOA)	521 ft.
Standard deviation	139 ft.
Length between perpendiculars (LBP)	481 ft.
Standard deviation	130 ft.
Deadweight tonnage (Summer loadline)	16,890 DWT
Standard deviation	9,500 DWT

Towing Boats

While sufficient data was available to accurately figure the average length of other types of vessels, the length of tow boats and their tows vary greatly. The typical inland and ocean-going tow boats may be approximately 75 and 115 feet overall respectively, but overall length of the tow may exceed 2,000 feet at times. Barges range in size from 100 to 450 feet, but average about 130 feet with a beam of about 50 feet. Under normal conditions, barges are towed on 600 to 800 feet wire cable. However, in heavy weather the length of wire cable

may be extended to up to 1,500 feet. Also, two or three barges may be towed, with 100 to 300 feet of cable between barges.

Therefore, a one hundred foot vessel, with 1,200 feet of towline, and three barges separated by 200 feet of cable would have an average overall length of 2,000 feet. Barges also have a tendency to swing about two beam widths to either side of the centerline under normal conditions. In heavy weather, barges have been known to actually pass the towing boat.

A normal length of approximately 1,100 feet was assumed for the overall length of tow boat and tow for encounter situations in this study, based on an estimate of length provided by Foss Launch and Tug Company, the largest single operator in the marine towing industry in the Puget Sound area. The average length of the barge train was assumed to be approximately 300 feet for use in the encounter rate model.

Miscellaneous Vessels

During the period of 14-20 April, 1974 there were 53 transits within the Puget Sound VTS by 29 miscellaneous vessels. Of these 29 vessels, sufficient information was available on only 20 of the vessels to compute average length. Thirty of the 53 transits were made by United States Navy and Coast Guard vessels, most of which were lane crossings of short duration. Average size of the vessels classified as miscellaneous were:[3]

Length overall (LOA)	147 ft.
Standard deviation	100 ft.
Length between perpendiculars (LBP) (estimated)	140 ft.

Ferries

The Washington State Ferries make approximately 180,000 one-way transits annually in the Puget Sound area. The Washington State ferry fleet consists of 18 active vessels of various sizes. During the Fall-Winter-Spring schedule seasons, 13 vessels were utilized on eight ferry routes which perpendicularly cross the VTS traffic lanes. The average size of the ferries employed were:[4]

Length overall (LOA)	324 ft.
Standard deviation	88 ft.
Length between perpendiculars (LBP) (estimated)	300 ft.

VESSEL SPEED

The average speed at which vessels operate within the Puget Sound area was determined from the vessels' individual transit cards for the week of 14-20 April 1974. All vessels entering the VTS indicate their estimated speed of advance (SOA), and also their estimated time of arrival (ETA) at the next check-in point of their transit. The actual speed of advance can therefore be calculated by dividing the distance between two points by the difference in check-in time at the points.

A speed profile was established for the four general classes of vessels within Puget Sound. The average speed and deviation from the average was calculated for both the vessels' estimated SOA, and the actual SOA. It must be stated that the actual SOA is based upon a vessel's assumed positions within the VTS, and cannot be regarded as highly accurate. (Indeed, a vessel's reported position could vary by several miles from its reported check-in point.) Nevertheless, the differences between vessels' reported SOA and the actual (calculated) SOA was found to be small.

Tankers

During the week of 14-20 April 1974, nine tankers made 17 transits within the VTS area. Of these transits, one vessels transit card was unable to be located. Based on the 16 transits, the following information was calculated:

	Estimated by Vessel	Actual as Determined from Check Points
Transit Speed	13.41 kts	13.52 kts
Standard Deviation	1.77 kts	1.92 kts
Speed Range (all vessels)	11-16 kts	11-17.5 kts

Freighters

During the week of 14-20 April 1974, 92 transits were made by freighters within the VTS.

	Estimated by Vessel	Actual as Determined from Check Points
Transit Speed	15.64 kts	15.82 kts
Standard Deviation	2.89 kts	3.05 kts
Speed Range (92 vessels)	7-23 kts	6.6-23 kts

Miscellaneous

Fifty transits were made by miscellaneous vessels, excluding the experimental hydrofoil High Point. (In the case of the High Point, the vessel crossed the traffic lanes at 45 kts on several occasions while undergoing testing in Puget Sound.)

	Estimated by Vessel	Actual as Determined from Check Points
Transit Speed	11.12 kts	11.10 kts
Standard Deviation	3.54 kts	3.9 kts
Speed Range (50 vessels)	3.5-20 kts	3.7-20.8 kts

Towing Boats

During the week of 14-20 April 1974 a total of 344 Tow Boat transits were recorded on cards filed at the VTS. Speed within this class of vessels covered the widest range, from less than two knots (for tugs with log tows) to 14 knots. Average speed was first determined by days of the week, to identify any large variations in speed as a result of different degrees of traffic density. All speeds utilized in these computations were the vessels own estimated SOA.

Date	Day	Average SOA	Deviation	Number of Recorded Vessel Transits
14 Apr	Sun	7.30	2.77	29
15	Mon	7.89	3.01	51
16	Tues	6.77	2.03	44
17	Wed	6.81	2.60	57
18	Thurs	7.08	2.40	62
19	Fri	7.41	2.86	50
20	Sat	7.48	2.35	50

While in no way conclusive, the average tow boat speed on Tuesday through Thursday is less than the daily average for the remainder of the week. Whether the reason for this difference is due to generally higher levels of vessel activity, weather, or other factors could not be determined from this sample, nor is it within the scope of this study to do so.

Neglecting any significant daily variations, the average speed for the sample size of 344 vessel transits is 7.24 kts, with a standard deviation of 2.59 knots.

Ferries

From September 1973 until June of 1974, thirteen Washington State Ferries were regularly assigned to eight routes within the Puget Sound area. From statistics provided by the Washington State Ferries Traffic Department, the average speed of these thirteen vessels has been estimated:

Transit Speed	15.85 kts.
Standard Deviation	4.1 kts.
Speed Range (13 vessels)	10-20 kts.

SUMMARY OF VESSEL CHARACTERISTICS

The results of the two-week survey to determine vessel physical and operating characteristics is summarized in the following table.

Table 2-4

Summary of Vessel Characteristics (Summary of the Results of a Two-Week Traffic Survey to Determine Characteristics.)

Vessel Class	Mean Velocity kts.	Standard Deviation kts.	LOA ft. (naut. mi.)	LBP ft. (naut. mi.)
Freighters	15.6	3.0	521 (.09)	481 (.08)
Tankers	13.5	2.0	609 (.10)	584 (.10)
Tow Boats	7.2	2.6	1100[1] (.17)	1100[1] (.17)
Barges	-	-	-	300[1] (.05)
Miscellaneous	11.1	3.5	147 (.02)	140[1] (.02)
Washington State Ferries	15.9	4.1	324 (.05)	300[1] (.05)

[1]Indicates estimated values

DAILY VESSEL DENSITY BY VESSEL CLASS

From the data obtained from the surveys of Week I and II, the average vessel transit hours were separated by type, to determine if any particular days of the week were more heavily trafficked by a particular class of vessel.

Table 2-5

Daily Average of Vessel Transit Hours by Vessel Class

Day	Two Week Average of Vessel Transit Hours (Percent of Daily Volume)				Daily Total (Percent of Weekly Total)
	Freighters	Tankers	Tow Boats	Misc	
Sun	68.5 (21.9)	11.5 (3.7)	218 (69.8)	14.5 (4.6)	312.5 (12.0)
Mon	52 (15.8)	11.5 (3.5)	250 (76.0)	15.5 (4.7)	329.0 (12.6)
Tues	47.5 (13.5)	20 (5.7)	246 (69.8)	39 (11.1)	352.5 (13.5)
Wed	51 (12.8)	29.5 (7.4)	295 (74.0)	23 (5.8)	398.5 (15.3)
Thurs	73.5 (17.0)	10 (2.3)	315 (72.8)	34 (7.9)	432.5 (16.6)
Fri	56.5 (14.5)	8.5 (2.2)	298 (76.6)	26 (6.7)	389.0 (14.9)
Sat	59.5 (15.2)	12.0 (3.1)	285.5 (72.9)	34.5 (8.8)	391.5 (15.0)
Total (percent of weekly total)	408.5 (15.7)	103 (4.0)	1,907.5 (73.2)	186.5 (7.2)	2,605.5 (100)

In general, it may be observed that during the two weeks under study the daily traffic breakdown by vessel class shows consistent results. Towing boats make up the bulk of the vessel transit hours, 73 percent of the total, with freighters making up 16 percent, miscellaneous seven percent, and tankers four percent. The two most obvious variations are relatively higher tanker transit hours on Tuesday and Wednesday, and higher Freighter transit hours on Sunday. Aside from these two exceptions, the weekly percentage breakdown remained consistent throughout the period.

From this information one may conclude that the general breakdown of vessel traffic underway at any period is made up of predominantly tow boat traffic (73 percent) and freighter traffic (16 percent) with the remaining 11 percent consisting of miscellaneous vessels and tankers.

FOOTNOTES

[1] _______, Lloyd's Register of Shipping 1973-1974, Lloyd's Register of Shipping Trust Corp. Ltd., (London, 1973).

[2] Lloyd's Register, and Jane's Fighting Ships 1969-70, V. B. Blackman, ed., Sampson Low, Marston & Co., Ltd., (London, 1969).

[3] Jane's Fighting Ships, and Washington State Ferries Fleet 1974, statistics compiled by Washington State Ferries.

[4] Washington State Ferries Fleet 1974 and Regular Vessel Allocations Fall-Winter-Spring Schedule, Washington State Ferries Traffic Department Bulletin, dated September 11, 1974.

[5] Ibid.

Chapter 3

VESSEL TRAFFIC DENSITY WITHIN PUGET SOUND

Introduction

In the previous chapter various physical and operating characteristics of Puget Sound area vessel traffic were presented. These characteristics (average vessel size and transit speed, and hourly traffic variation) provide a profile of the manner in which water-borne commerce moves. In this chapter, the general volume of vessel traffic will be identified by vessel class and geographical area. Information obtained from a one-month survey of vessel movements will provide the basis for an estimate of the overall encounter rate within the Puget Sound region.

UNITED STATES COAST GUARD TRAFFIC DENSITY SURVEY

In an attempt to identify areas of the Puget Sound region most conducive to radar surveillance, the Puget Sound VTS produced a Traffic Density Survey for the month of June 1973. The information for this survey was extracted manually from the file of vessel transit cards for the month of June, and a count was made of the number and types of vessels which transitted between known check points. The goal of the Traffic Survey was to give a general representation of the relative traffic volume in the various portions of the system, so that highly-trafficked regions could be identified and prioritized

for higher levels of traffic control.

While the results of the Traffic Survey are in no way definitive of all vessel movements of the four major classes of vessels, the survey does illustrate the traffic patterns of a large segment of the water-borne commerce within the region. Estimates of the level of participation in the VTS at the time of the survey by the Coast Guard officials were approximately 70-80 percent for Tow Boats and 95 percent for all other vessels. At the time of the survey participation in the VTS by most classes of vessels was on a voluntary basis. The Puget Sound VTS had been in operation for less than one year, and user participation was still increasing, as is indicated by monthly totals of traffic volume. It is not within the scope of this paper to identify the exact number of vessels which transitted particular areas or waterways. Indeed, figures on transits do not exist in any form other than those maintained by the Coast Guard VTS. The data for the June Traffic Density Survey was compiled at the expense of approximately 30 man-days, and, while it was not intended to be an exact study, the information will be utilized as a basis for general assumptions regarding traffic density. The results of the Coast Guard Traffic Density Survey of June 1973 are depicted in Figures 3-1 through 3-4 on the following pages.

Traffic totals for the month of June 1973 were compared to the average for the twelve months from June 1973 to May 1974. No attempt has been made to identify any biases or seasonal variations in the 12 month period. Certain variations

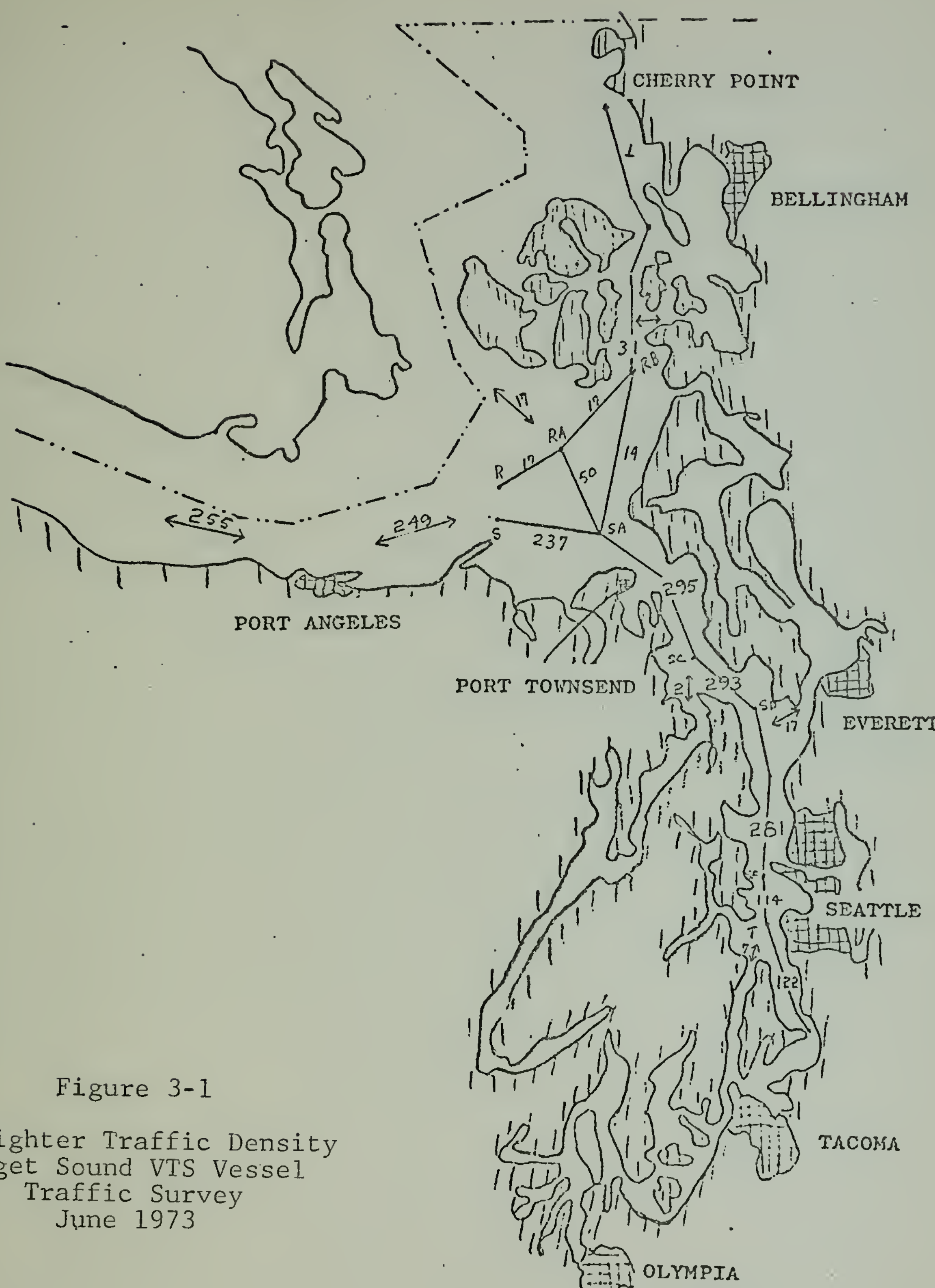

Figure 3-1

Freighter Traffic Density
Puget Sound VTS Vessel
Traffic Survey
June 1973

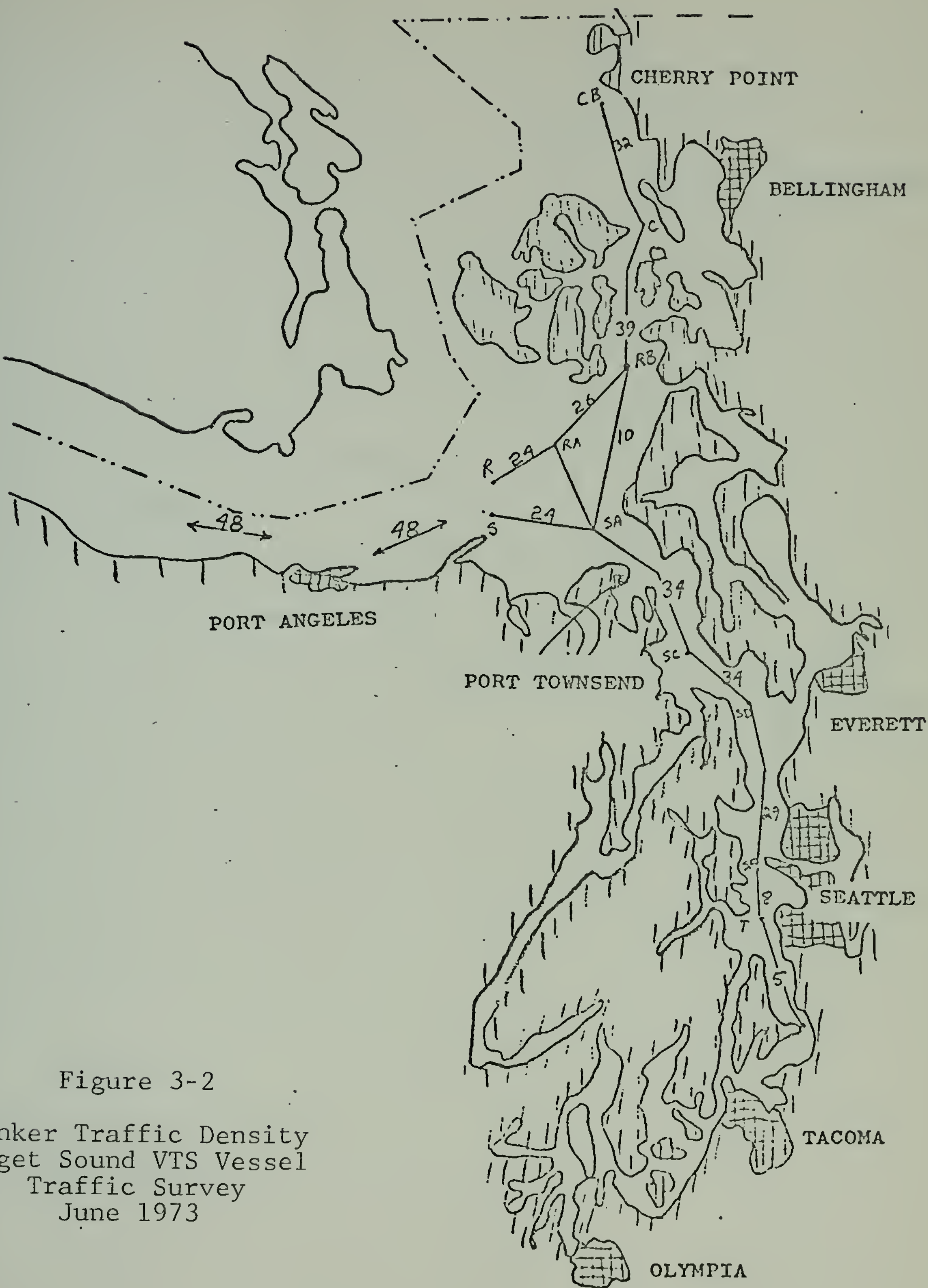

Figure 3-2

Tanker Traffic Density
Puget Sound VTS Vessel
Traffic Survey
June 1973

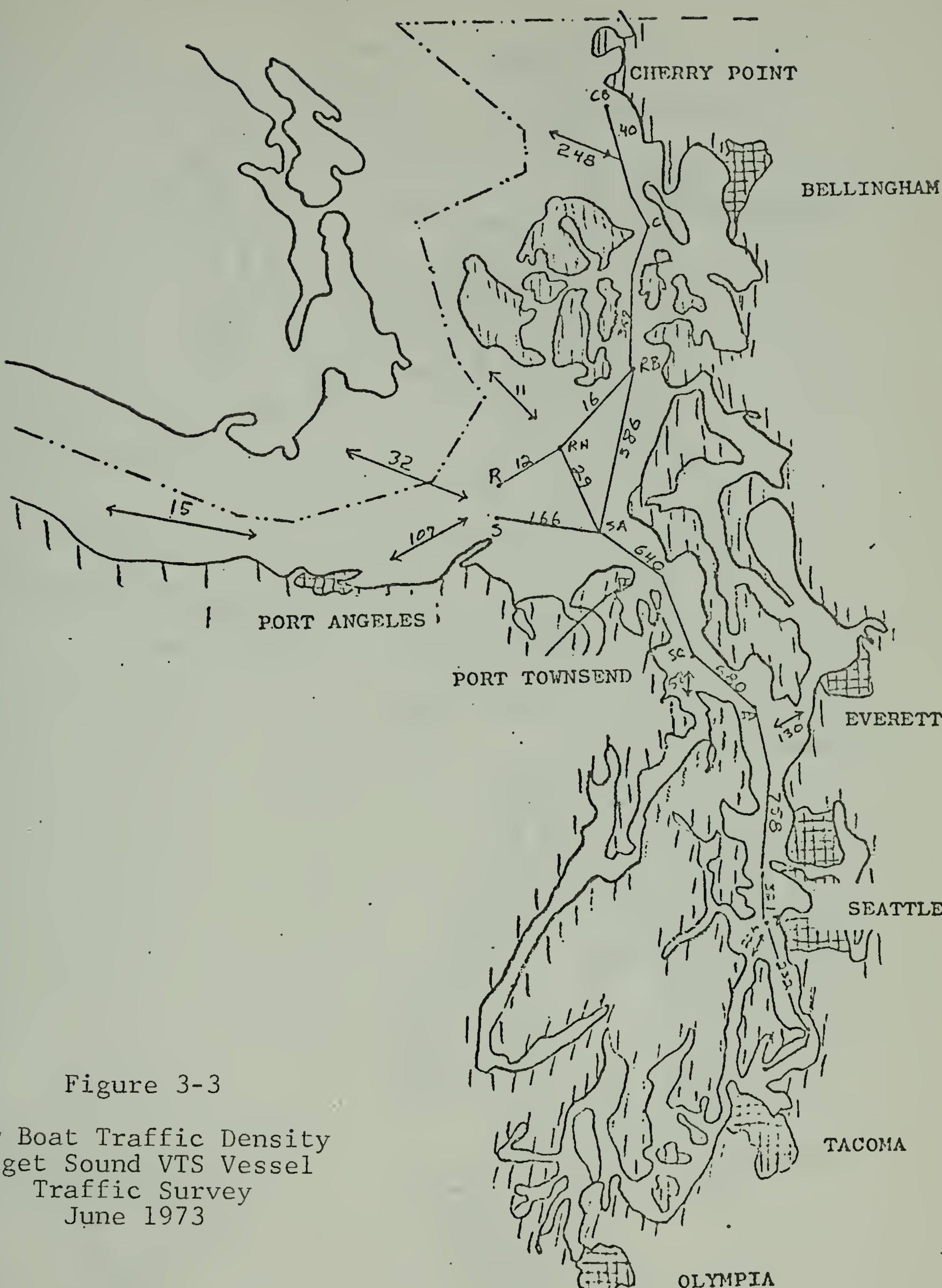

Figure 3-3

Tow Boat Traffic Density
Puget Sound VTS Vessel
Traffic Survey
June 1973

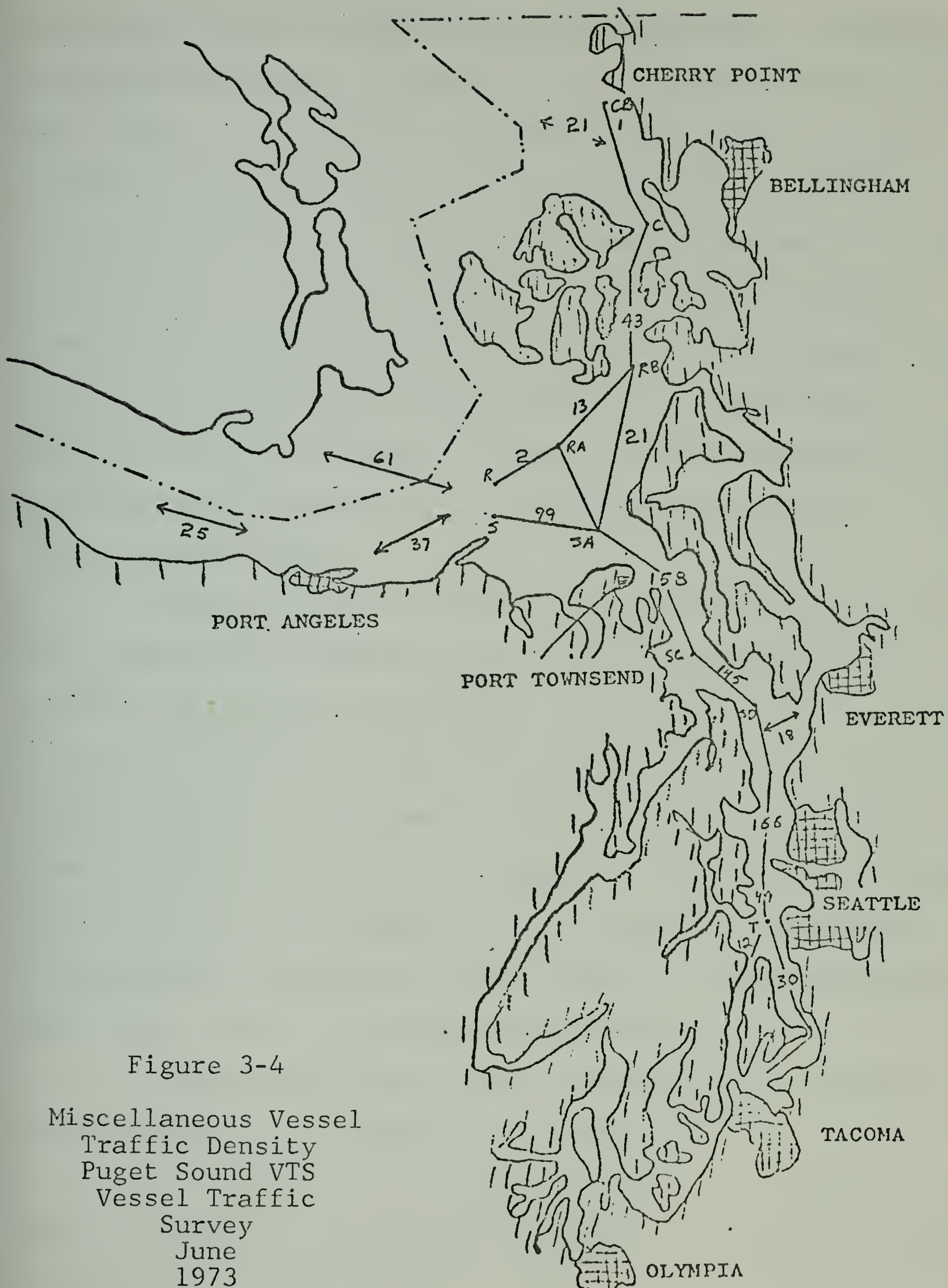

Figure 3-4

Miscellaneous Vessel
Traffic Density
Puget Sound VTS
Vessel Traffic
Survey
June
1973

may exist, as in higher numbers of excursion boats and passenger ferries underway during summer months. Furthermore, seasonal variations in tanker, tow boat, and freighter traffic may exist, as well as variations in traffic due to fluctuations in foreign commerce. Increased traffic may have resulted from conditions such as increased commodity shipments to the Soviet Union and Peoples Republic of China, and increased imports of petroleum products by sea due to limitations of the import of Canadian petroleum by pipeline. Furthermore, abnormal traffic is likely to result from labor disputes in ports such as Vancouver B.C., San Francisco, or other United States ports.

While in no way seeking to ignore these variations, this paper will assume that over a one year period, such traffic fluctuations are minimal. Furthermore, the variations of participation for users of the VTS will also be assumed to be minimal, that is, user participation for the period under investigation has reached its highest level. No more vessels which have not participated (due to lack of required VHF communications equipment, or new Federal or State requirements) will have joined the ranks of participants.

The month of April 1974, was utilized for encounter rate modeling, for the following reasons:

1. The data was relatively current, and therefore it was assumed that a very high percentage of user participation existed during that month.

	June 1973 Transits	12 Month Average of Transits	April 1974 Transits
Freighters	360	327.9	350
Tankers	62	75.9	83
Tow Boats	1,369	1,354	1,519
Miscellaneous	301	252	231
Totals	2,092	2,010	2,183

2. The total traffic volume for the month was high, exceeding the average by approximately nine percent. This may be a result of increased user participation, as well as trends toward an overall increase in traffic volume. Tanker traffic exceeded the monthly average by seven vessel transits, and exceeded the month of June 1973 by 21 vessels.

The June 1973 Traffic Survey data was therefore assumed to be a base month, and traffic volume was assigned an index of 100.0 for all classes of vessels. Traffic density was assumed to vary linearly throughout all areas of Puget Sound, based on the June 1973 Survey. Traffic density therefore was assumed to be a function of the number of vessel transits during the month, and the density within the region was represented as a function of the June 1973 traffic density.

Using these assumptions, the traffic volume for a class of vessels within a segment of the Puget Sound region will be represented by the figures extracted from the June 1973 Survey, multiplied by the index of April 1974 Transits as a fraction of June 1973 Transits.

Vessel Class	June 1973 Transits	April 1974 Transits	Index
Freighters	360	350	1.0
Tankers	62	83	1.3
Tow Boats	1,369	1,519	1.1
Miscellaneous	301	231	.8
Total	2,092	2,183	1.04

This index was utilized in subsequent chapters to convert traffic volume from the June 1973 Traffic Density Survey to April 1974 traffic volume. Encounter rates for April of 1974 were then estimated utilizing the encounter rate model which will be developed in the following chapter.

Chapter 4

DEVELOPMENT OF AN ENCOUNTER RATE MODEL

Introduction

In recent years, world-wide attention has been focused on the increasing number and severity of marine accidents. A significant portion of these accidents are collisions, and the maritime nations of Japan and Great Britain have taken the lead in an attempt to identify the nature and causes of collisions, as well as to devise methods to reduce their growing number. A considerable body of knowledge has accumulated over a relatively short span of time as a result of studies conducted in both Japan and Great Britain regarding vessel collisions.

In this chapter two recent studies which attempted to predict the probability of vessel collisions in Puget Sound will be examined in light of the data previously presented in Chapters 2 and 3. A more appropriate model will be presented which can more accurately simulate the real-world conditions of Puget Sound traffic. This model which simulates the physical situation of vessel traffic in a waterway is based on a technique derived for simulating encounter rates in air traffic control, as modified by the results of recent studies conducted in Japan on vessel traffic and collision rates. In subsequent chapters, the previously presented information on Puget Sound vessel traffic patterns and operating character-

istics will be used with this model to identify the collision potential which exists in the various areas of Puget Sound.

PREVIOUS COLLISION STUDIES IN THE PUGET SOUND AREA

Two recent studies, one published by the Marine Systems Center of Honeywell Inc., and the other by Vagners and Mar in Oil on Puget Sound, have attempted to define the probability of vessel collisions within the Puget Sound area. Both studies have utilized the mathematical modelling technique developed by the Sperry-Piedmont Company (hereafter referred to as the Sperry Model) to predict collision probability within a channel. In addition to the Sperry Model, the application of a model analogous to a two-dimensional free gas model was utilized to predict the probability of a collision in the areas of the Puget Sound region in which vessel traffic was assumed to exhibit random motion, as opposed to more predictable path motion.[1]

The Sperry Model is essentially a parallel path model. The application of this model to vessel traffic within Puget Sound was based on the premise that all ships utilizing the waterways maintain a course which is parallel to the channel centerline. Vessels were assumed to be uniformly distributed across the width of the entire waterway, and to present a potential collision situation when the waterway is occupied by two vessels on opposing courses. The probability of a collision was determined by the ratio of the vessels' beam width to the width of the waterway, and therefore is a

function of the physical cross sectional area which a vessel occupies in a waterway.[2]

The Sperry Model, as applied by both Honeywell and Vagners and Mar, did not take into account the collision potential presented by overtaking situations in a waterway, nor did it make any provision for the fact that a reasonably effective method of channel separation would be established which significantly reduces the number of head-on encounters in the Puget Sound area.[3] Potential collisions which might result from vessels crossing the waterway were also ignored in these two applications of the Sperry Model. By applying this model to the existing situation of vessel traffic in Puget Sound, one can expect almost no encounters, and consequently no collisions, as a result of the recently established one-way traffic separation scheme for the majority of this region.

The data utilized with the Honeywell application of the Sperry Model differed significantly from the data on vessel movements developed in the previous chapters. Honeywell estimated total Puget Sound traffic to equal twenty deep-draft vessel transits per day, and ten barge transits. All vessels were assumed to be transitting at a speed of eight knots, and every vessel was assumed to have encountered eight ferries in the waterway during each one-way transit.[4] The data on vessel movements utilized by Vagners and Mar was derived from United States Army Corps of Engineers statistics published in Waterborne Commerce of the United States for 1967. The number of ship movements in each channel was estimated as a

percentage of the total vessel movements throughout the entire Puget Sound region, and that percentage was determined by total internal and external commercial tonnage recorded by each port along the channel.[5] All vessels were assumed to be operating at a transit speed of fifteen knots.[6]

Both the Honeywell study and that of Vagners and Mar utilized a model which estimated the number of collisions in a waterway as being analogous to the number of collisions between molecules randomly moving in a volume of gas. This two-dimensional free gas model was applied to a large area at the eastern end of the Strait of Juan de Fuca, between Haro and Rosario Strait and Admiralty Inlet. Vessels transitting this area were assumed to simulate random motion, and the probability of collision was determined to be a function of the ratio of the physical area occupied by a vessel to the entire area of the waterway. Vessels were assumed to be transitting at normal speed. Vagners and Mar assumed that an average vessel was 300 feet in length, with a beam of 75 feet. The Honeywell Study assumed an average collision cross section of 300 feet for each vessel.[7]

The previously cited studies which estimated the number of vessel encounters within the Puget Sound region were based on broad assumptions regarding vessel traffic characteristics. By utilizing the data which was derived from the two-week traffic analysis, as well as that of the Coast Guard June Traffic Density Survey, several of the assumptions or estimates upon which this study was based can be modified, and

a more accurate prediction can be used. The following points can therefore serve to improve the accuracy of the predictive model:

1. A more accurate traffic density pattern can be derived in place of estimates of traffic density.

2. More accurate estimates of average vessel size and transit velocity can be utilized.

3. Random distribution of two-way traffic within the width of the waterway can be ignored. While instances of opposing traffic still exist, the adherence by vessels to the one-way Traffic Separation Scheme has been uniformly accepted, thereby reducing the number of head-on encounters.

4. Encounters can be estimated for known crossing traffic and for traffic intersections.

While the Honeywell and Vagners and Mar studies did not claim to be accurate predictive models, their results have been widely disseminated and utilized in an attempt to provide some type of quantitative estimates of future accident statistics. The Oceanographic Commission of the State of Washington, in _Risk Analysis of the Oil Transfer System_, utilize these same modelling techniques as their basis to predict oil spills resulting from collisions. These studies have also been cited by William M. Ross in _Oil Pollution As An International Problem_ (University of Washington Press, 1973).

BASIS FOR AN ENCOUNTER RATE MODEL

Development of the Model

The basis for the model that will be presented in this study is that used in predicting the number of mid-air collisions in a defined air space. The fundamental principle is that of a vessel (or aircraft) of velocity V moving through an area A containing N objects, evenly distributed. If there exists a near miss minima, which will be initially defined as D/2, and much greater than the vessel dimensions, then the vessel may be considered as a discrete point source. An encounter, then, is analogous to a Near Mid-Air Collision (NMAC), and is defined as having occurred when two vessels, represented as discrete points, come within a specified distance from each other. This distance, D/2, is called the horizontal near miss distance in air traffic control.[8]

A vessel moving through area A will sweep an effective near-miss path of area VD per unit of time. Within this path there will be on the average VDN/A stationary obstacles. The moving vessel will have encountered VDN/A obstacles per unit of time. If the obstacles are not stationary, but are moving with a certain velocity, then the rate of encounter becomes $\bar{V}_R DN/A$, where $\bar{V}_R$ is the mean relative velocity between the intruding vessel and the N obstacles evenly distributed within the area A.

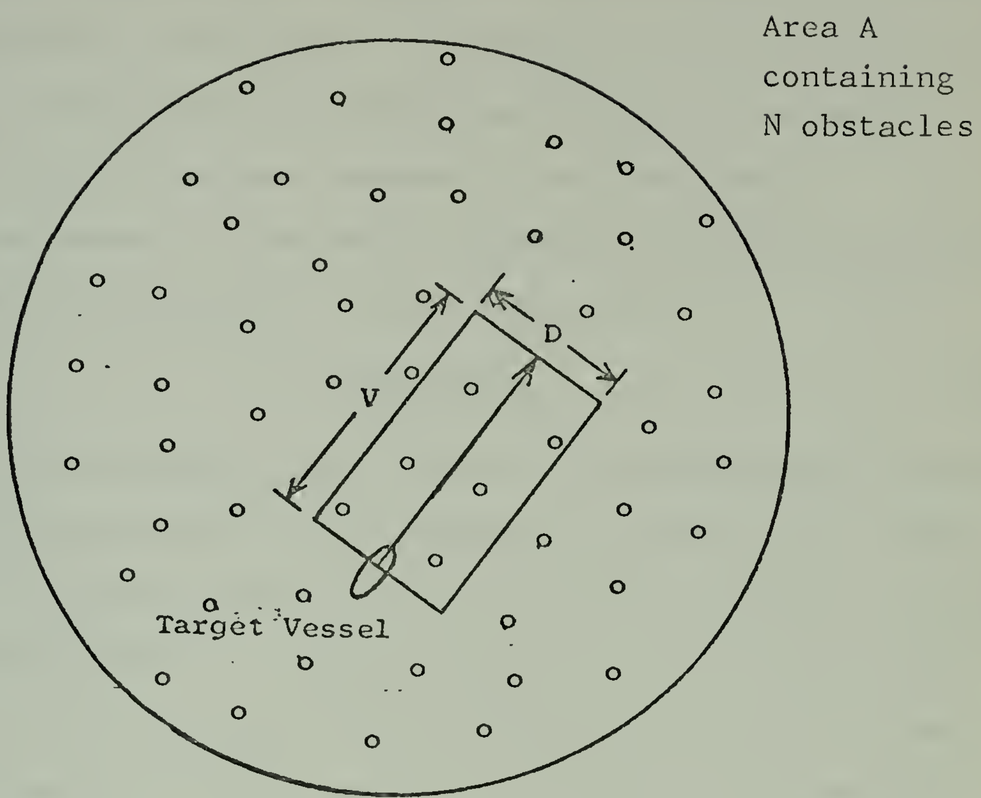

Figure 4-1

Representation of Vessel Encounters in an Area

The expected number of encounters, during the time interval T, between one vessel and a stream of vessels of number N distributed uniformly over an area A is

$$E = \bar{V}_R DNT/A \tag{1}$$

where $\bar{V}_R$ is the mean relative velocity between the intruding vessel and members of the group.[9]

From this basis, one may proceed to define the number of encounters between two groups of vessels evenly distributed

over an area A. With two groups of vessels numbering N_1 and N_2 respectively, the rate of encounter between members of one group and those of the other is $\bar{V}_R D N_1 N_2/A$ encounters per unit of time. The velocity of the encounter, $\bar{V}_R$, is the mean relative velocity between members of the two groups.

The number of encounters between the two groups of N_1 and N_2 vessels during the time interval T is

$$E = \bar{V}_R D N_1 N_2 T/A \qquad (2)$$

where $\bar{V}_R$ is the mean relative velocity between the two groups.

The encounter rate of members of a group with other members of the same group can be developed in a similar manner, in that each member of the group encounters the (N-1) other members at a rate of $\bar{V}_R D(N-1)/A$ encounters per unit of time. For all N members of the group, this results in an encounter rate of $\bar{V}_R DN(N-1)/A$ encounter per unit of time. This formula counts every encounter two times, once for each of the two vessels involved in the encounter. The actual number of encounters is

$$E = \bar{V}_R DN(N-1)T/2A \qquad (3)$$

during time interval T. For a large group of vessels, (N-1) is approximately equal to N, and the number of encounters between members of the same group is

$$E = \bar{V}_R DN^2 T/2A \qquad (4)$$

where $\bar{V}_R$ in this case is the deviation of the mean relative speed between vessels moving at the same mean speed. This

particular case can be considered as an overtaking situation in a waterway made up of similar vessels travelling at the same speed in the same direction. If all vessels are widely spaced, and travelling at the exact same speed, then relative velocity, $\bar{V}_R$, is equal to zero, and no encounters occur. However, if vessels are travelling at speeds distributed about a mean speed, then the standard deviation of the speed is a close approximation of the relative speed, and encounters will occur.[10]

It is useful at this point to define ρ, the mean vessel density, as the mean number of vessels per unit area. The quantity ρ can be computed for any group of vessels from a count of vessels present in an area at a discrete time interval. Vessel density ρ may be computed from N/A, or from the traffic volume, Q. In the latter case, the traffic volume for various areas of Puget Sound have been determined during a one-month period, as have the mean speed at which vessels transit. Therefore ρ for a particular class of vessel transitting a particular region can be determined from the equation

$$Q = \rho \bar{V}_w \tag{5}$$

or

$$\rho = Q / V_w \tag{6}$$

where Q is the traffic volume in vessels per unit time, $\bar{V}$ is the mean transit speed of the vessels, and w is the width of the waterway.

Substituting the value of mean vessel density into equation (1), the number of encounters between a single intruding vessel and a group is

$$E = \bar{V}_R D \rho T \qquad (7)$$

The number of encounters per unit area between two groups, equation (2), becomes

$$E = \bar{V}_R D \rho_1 \rho_2 T \text{ encounters per unit area,} \qquad (8)$$

where ρ_1 and ρ_2 are the density of respective groups of vessels. Similarly, the number of encounters within a single group of vessels, equation (4) becomes

$$E = \tfrac{1}{2}\bar{V}_R D \rho^2 T \text{ encounters per unit area.}^{11} \qquad (9)$$

Computation of Relative Velocity

Encounter rate modeling consists of an attempt to identify the number of conflicts, or encounters, in two general situations. Those situations can be described as the conflicts which result from a stream of vessels of a particular velocity and density passing through another stream, and the conflicts which result from a stream passing through a swarm of vessels. In the latter case, the swarm is assumed to be on random headings. The differences between these two cases is especially significant when attempting to identify the relative velocity used to compute encounter rates. G.T.A. May presents a full discussion and graphical representation of the dependence of relative velocity on the mean speeds of the streams and swarms.[12] While acknowledging the significance of his derivation, it is not at all obvious that the patterns of vessel traffic within the Puget Sound area are representative of vessels moving in random directions. With the option of describing existing

vessel traffic as either streams or random swarms of vessels, a logical choice appears to be the former. Within certain confined geographical regions, the modeling of a swarm may appear more appropriate, as in fishing vessels moving within a fishing ground, or harbor traffic in Elliot Bay for example. Nevertheless, the encounter rate modeling in this study will be based on the assumption that actual vessel traffic within Puget Sound closely conforms to the concept of vessels moving in streams of various densities and at various velocities.

The assumption that vessel traffic moves in streams simplifies the types of possible encounters which are to be modelled. The possible situations which exist within the area consist of overtaking encounters within a stream, merging or crossing of two streams, and head-on encounters between two opposing streams. Proceeding under these assumptions, and working from a basis of observed vessel densities and velocities, only relative velocity, $\bar{V}_R$, is required to compute the theoretical encounter rates for various combinations of streams and individual vessels by applying three general formulas.

The simplest situation is two streams intersecting at an angle θ, one stream of vessels travelling at a mean speed of $\bar{V}_1$ and one of mean speed $\bar{V}_2$. Then to a reasonable approximation relative velocity, $\bar{V}_R$, can be computed from:

$$\bar{V}_R = \sqrt{\bar{V}_1{}^2 + \bar{V}_2{}^2 - 2\bar{V}_1\bar{V}_2\cos\theta}.$$

Of this general form, there are four special cases:

(1) $\bar{V}_1 = \bar{V}_2 = \bar{V}$ (streams with the same mean speed):

$$\bar{V}_R = \bar{V}\sqrt{2 - 2\cos\theta}$$

(2) $\theta = 0$ (for example, slower vessels travelling along the same route with faster vessels):

$$\bar{V}_R = \left|\bar{V}_1 - \bar{V}_2\right|$$

(3) $\theta = 90°$ (Crossing streams):

$$\bar{V}_R = \sqrt{\bar{V}_1^{\,2} + \bar{V}_2^{\,2}}$$

(4) $\theta = 180°$ (shipping travelling in opposite directions along the same route):

$$\bar{V}_R = \bar{V}_1 + \bar{V}_2$$

In general, none of these formulas will be precisely correct, but the approximations will be good unless θ is small and the range of the velocities for which $\bar{V}_1$ and $\bar{V}_2$ are means is small compared to the magnitude of $\bar{V}_R$. (In the limiting situation of $\theta = 0$ and $\bar{V}_1 = \bar{V}_2$, $\bar{V}_R = 0$, and a prediction of no encounters results from applying the formulas above.)

The limiting case noted in parentheses above is in fact the one case for which the use of mean speeds will not suffice, that of encounters among members of the same stream (overtaking in a group of vessels travelling in the same direction). Here relative velocity, $\bar{V}_R$, must be calculated from observed differences in speed.[13]

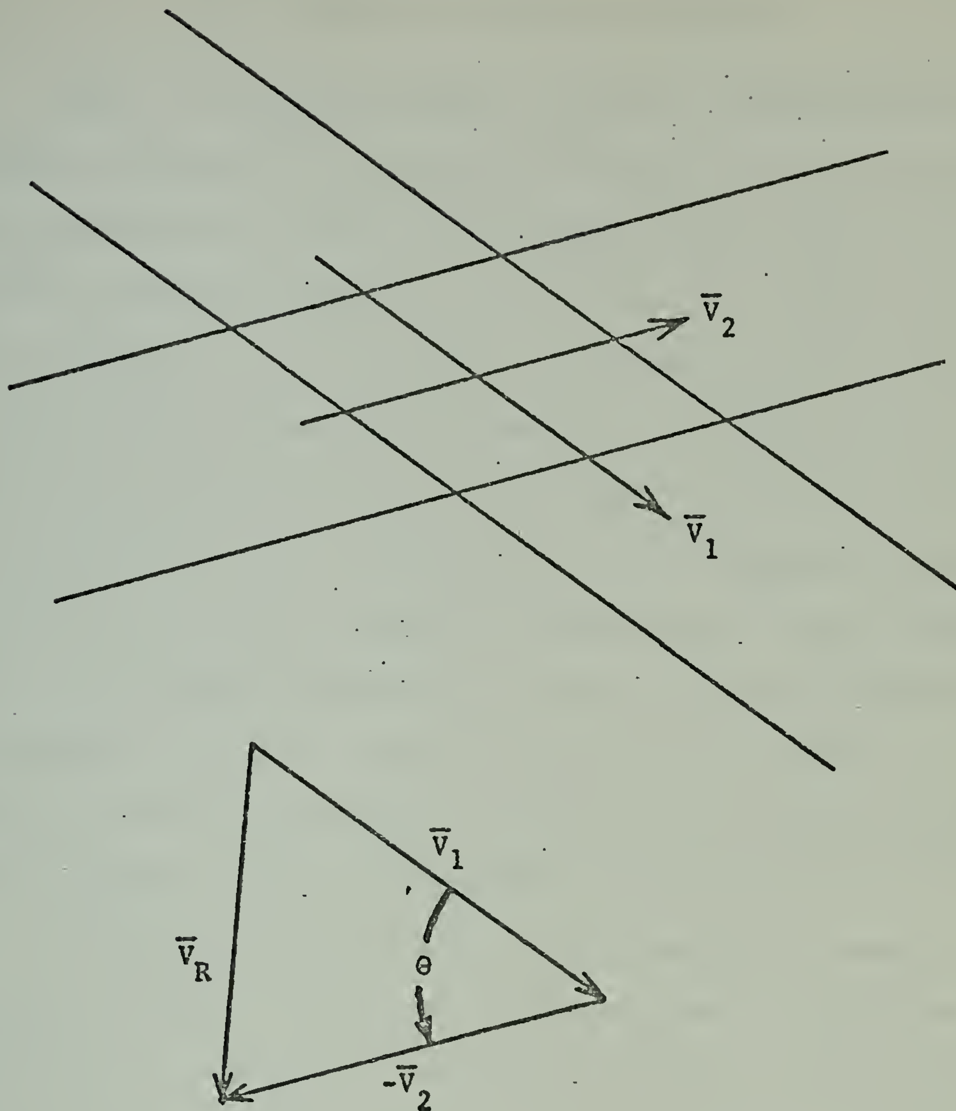

Figure 4-2

Relative Velocity of Intersecting Streams

THE CONCEPT OF EFFECTIVE DOMAIN

Due to increasing vessel traffic, accompanied by an increasing frequency of vessel collisions, in the straits and harbor approaches of Japan, the Japanese Government has sponsored extensive studies in an attempt to analyze vessel traffic accidents. As a result of several of the studies, Fujii and Shiobara have determined that a relationship exists between the collision rate and the traffic volume, and that this collision rate is a function of linear density, speed, and tidal current. Further studies indicate that there exists a general relationship between the rate of vessel collisions and the frequency of evasive action to avoid collisions. Extensive statistical surveys have shown consistent agreement between accident theory and existing conditions.[14]

A further piece of information regarding vessel encounter rates and collisions was published by Fujii and Tanaka in 1971. Briefly, their work resulted from an attempt to identify the traffic capacity of a waterway. From 1964 to 1966 studies were conducted in Japan to measure the speed, length, and separation of vessels in various waterways. Observation of traffic were made utilizing Programmed Radar Photography, in which a 35 mm camera photographed a high resolution radar scope every 10 seconds. By synthesizing the results of these observations, a phenomenon was observed. This phenomenon was described as an existing boundary surrounding vessels in heavily-trafficked waterways, and this boundary was termed the effective domain.[15]

Fujii and Tanaka described effective domain as a psychological barrier or boundary surrounding a vessel, and analogous to the repulsive forces of two charged particles of the same sign. The repulsive forces cause an avoiding motion, while the attractive forces cause groupings of vessels, much as in crystal growth. The definition of this boundary was determined by long observation and elaborate data treatment, and was found to have significant influence on capacity of a waterway.[16]

Effective domain has been represented in Figure 4-3, which shows the distribution of separation between centers of ships whose lengths are between 70m and 140m. The distribution was found not to differ from the left to right quadrant. The presence of an effective domain is clearly evident, and it was determined to be a half-ellipse having a semi-axis major of 500m and semi-axis minor of 300m.[17]

Six series of two-week observations were made by Fujii and Tanaka to obtain the size of the effective domain. The results of these observations for the effective domain corresponding to vessel length L at normal speeds were:

$$r = 7L \pm L \tag{10}$$

$$s = 3L \pm 0.5L \tag{11}$$

where r is the semi-axis major, and

s is the semi-axis minor.

Tanaka and Fujii further observed that the ships navigating congested waterways proceeded at approximately their normal sea speed.[18]

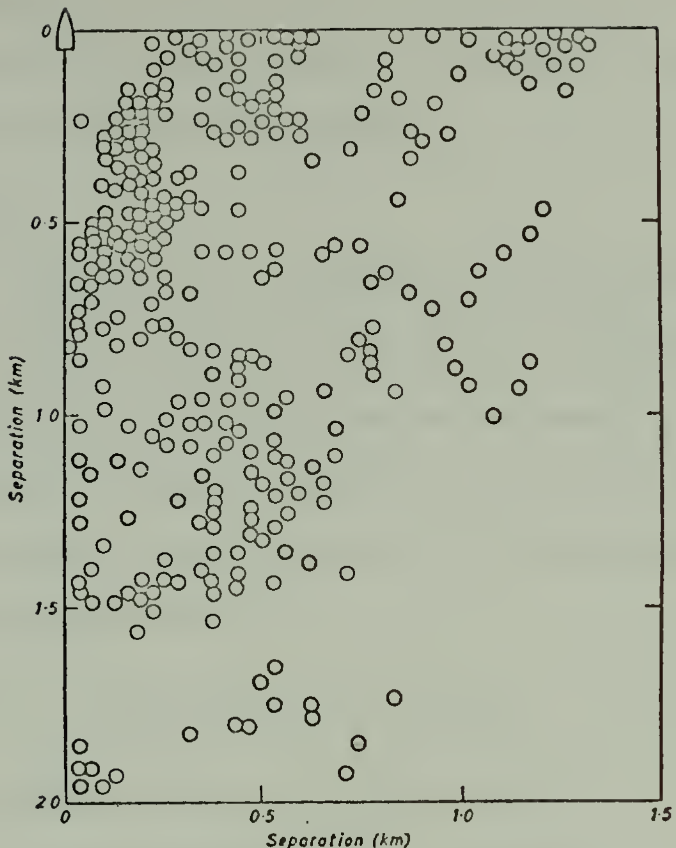

Figure 4-3

Distribution of Vessel-Vessel Clearance Distances

This illustration shows the distribution of separation between centers of ships whose lengths are between 70 m. and 140 m. Following the procedure already described for determining the boundary of the effective domain, it is seen to be a half-ellipse having a semi-axis major of about 500 m. and semi-axis minor of about 300 m.

Source: Fujii and Tanaka, "Traffic Capacity."

The results of the observations by Fujii and Tanaka, coupled with results of other Japanese studies with respect to the phenomenon of effective domain as it effects traffic safety, are summarized in the following pages.

Traffic Capacity

Traffic capacity of a waterway is reached when a waterway is so crowded that overtaking is almost impossible, and vessels form into groups with almost equal speed. In a one-way channel, under ordinary navigating conditions for vessels of almost the same size, L, and speed, V, the basic capacity, C_{bas} (L,V) can be defined as

$$C_{bas}\ (L,V) = W \rho_{max} V \tag{12}$$

where L is the length between perpendiculars

W is the width of the waterway

ρ_{max} is the maximum density.[19]

The maximum density is calculated from the size of the effective domain. Since the separation between centers of vessels must equal or exceed the size of effective domain, the maximum density obtained by closely packing ellipses of this size will be:

$$\rho_{max} = 2 / \sqrt{3}\ \ rs \tag{13}$$

where $2 / \sqrt{3}$ is the close packing ratio.[20]

Influence of Weather and Sea Conditions

Reduced visibility seems to slightly increase the size of the effective domain. Studies have shown that the mean speed of vessels in poor visibility is not appreciably smaller than their normal transit speed.

Expressions for the influence of tidal current on the size of effective domain were developed by Tanaka. It was found that the influence of tidal currents on capacity was small, especially for large vessels.[21]

Influence of Route Conditions

Several attempts have been made to define the effective domain of an obstacle. Though little data was available, Fujii and Tanaka suggest that the following relationships may be valid:

effective separation from a tower to a ship: approximately 4L,

effective separation from a buoy: approximately 2L,

effective separation from an artificial island: 5L.

Vessels of Dissimilar Size

Continued observations on the separation between vessels of different length showed the effective domain to be determined by $r = 7L'$ and $s = 3L'$, where

$$L' = ((L_1{}^2 + L_2{}^2) / 2)^{\frac{1}{2}} \quad (14)$$

[22]

Fujii and Tanaka infer that the effective domain for towing vessels is separate and distinct from that of the tow.

While not specifically stated in those terms, they do state that there appears to exist an effective domain for towed rafts or groups of barges. In this event, the effective domain of the towing boat and the barge combination could be represented as a chain of effective domains.[23]

Separation of Vessels on Reciprocal Courses

Fujii and Tanaka state that the size of effective domain for vessels in head-on encounters and crossing situations has not yet been adequately determined, although preliminary studies by Toyoda have estimated the effective separation distance to be approximately 4L.[24]

THE APPLICATION OF EFFECTIVE DOMAIN TO COLLISION RATES

The concept of the effective domain of a vessel was applied to collision rates and to the frequency of evasive action by Fujii and Shiobara. Statistical surveys of heavily trafficked straits and narrows supported the theory, and served to calibrate the model developed by Fujii.[25]

The general formula for determining the number of collisions in a waterway, determined by Fujii, takes the same form as that used by May to model Near Mid Air Collisions, equations (7), (8), and (9). Fujii determined the number of collisions in a waterway, N_{col}, to be a function of velocity, density, and the "geometrical collision diameter."[26] The formula is applied to two theoretical groups of vessels of the same size L_1 and L_2, and of the same velocities, V_1, and V_2 (the velocities are represented as vectors). The groups are

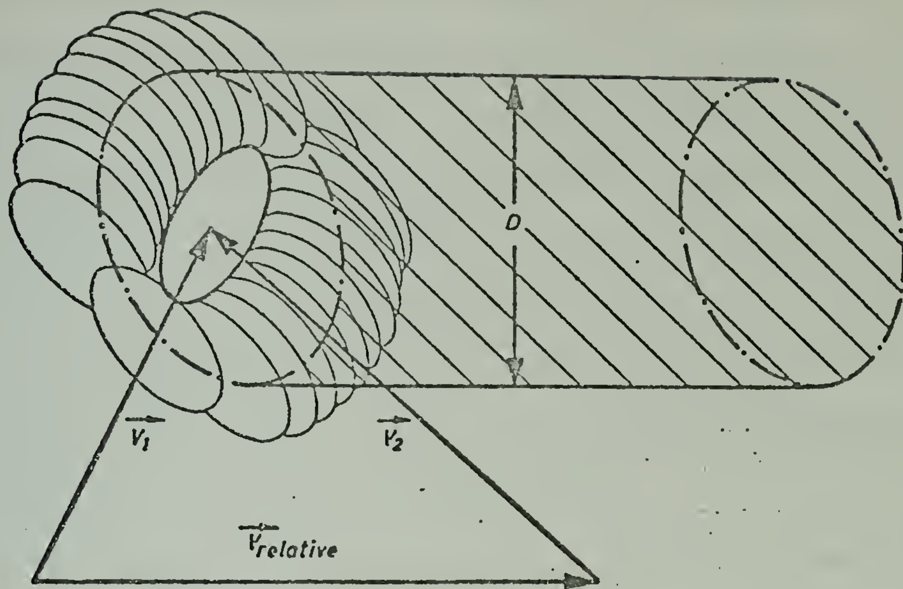

Figure 4-4

The Geometry of Collision

The geometrical collision diameter, D, is the length of the projection of chained domain to the direction perpendicular to the direction of the relative velocity.

Source: Fujii and Shiobach, "The Analysis of Traffic Accidents."

sailing on random courses. In Figure 4-4 the number of collisions with a ship belonging to the first group in unit time is equal to the number of centers of vessels belonging to the second group within the area swept out in unit time by the figure enclosed with the dotted line when it moves with a speed $\left|V_1 - V_2\right|$, i.e. the number of vessels of the second group in the hatched area. The number of collisions is: $D \rho_2 \left|V_1 - V_2\right|$, where ρ_2 is the traffic density and D is the "geometrical collision diameter."[27]

The number of collisions, N_{col}, in the time interval T is

$$N_{col} = \rho_1 \rho_2 D \left|V_1 - V_2\right| A T \tag{15}$$

where A is the area of the waterway. Fujii introduces the concept of probability, and rewrites equation (15) as:

$$N_{col} = \int_o^T \iint_A \tfrac{1}{2}(\rho_1 + \rho_2)^2 \; PD \left|V_1 - V_2\right| dA \, dt \tag{16}$$

where P is the probability factor. Terms containing $\rho_1^{\,2}$ and $\rho_2^{\,2}$ vanish since the relative speed of vessels in each group is zero. The term PD, defined as the collision diameter, is a function of the size of the vessel and the angle between courses.[28]

The frequency of evasive action can be obtained from equation (16) by replacing PD with the evasion diameter E_m, which is equal to the effective domain of the vessel.[29]

THE DETERMINATION OF COLLISION DIAMETER

From the relation of the collision number, N_{col}, to the size of the vessel Fujii assumed that the collision diameter PD is proportional to a ship's length. When this approximation is valid, the expression for the collision number which includes four components of linear density (east, west, north, and south) becomes:

$$\begin{aligned} N_{col} = {} & \tfrac{1}{2}\alpha V PD_{co} T \iint_A (\rho_E + \rho_W + \rho_S + \rho_N)\, dA \\ & + 2\, V PD_{out} T \iint_A (\rho_E \rho_W + \rho_N \rho_S)\, dA \\ & + \sqrt{2}\, V PD_{cross} T \iint_A (\rho_E \rho_N + \rho_E \rho_S + \rho_W \rho_N + \rho_W \rho_S)\, dA \end{aligned} \tag{17}$$

The first term in equation (17) corresponds to the co-directional collisions, the second term to the anti-directional collisions, and the last term to the crossing collisions. The relative speed in the first term is αV, which is equal to the standard deviation about the mean speed. In the second term, relative velocity is 2V, and in the last term it is $\sqrt{2}\ V$.[30]

Fujii and Shiobara utilized equation (17) to calculate the collision diameter, PD, for collisions between vessels in two cases, and their results were fairly consistent based on vessel traffic observations and existing accident statistics. The general collision diameters were estimated to be

$PD_{co} = 10^{-4}L$ for the co-directional case

$PD_{out} = 2 \times 10^{-4}L$ for the anti-directional case

These figures were interpreted to mean that skillful maneuvers by ship operators decreases the collision number to about 1/10,000, since the geometrical collision diameter is of the same order as L.

Fujii and Shiobara therefore concluded that there exists a close relation between the number of collisions and the number of times vessels take evasive action to avoid entering other vessels' effective domain. They concluded that one evasive action in 100,000 may fail, thereby resulting in a collision.[31]

FOOTNOTES

[1]Honeywell Marine Systems Center, Automated Marine Traffic Advisory Systems, Their Need and Implementation, Document 2330, 29 July 1971, and Juris Vagners and Paul Mar, Oil on Puget Sound, University of Washington Press (Seattle, 1972). For the full model development see Sperry Piedmont Company, Final Report Lookout Assist Device Feasibility Studies, Vol. I, Section 3, Contract No. MA-3374, August 1965.

[2]Honeywell, Op. Cit., p. 6 and Vagners and Mar, Op. Cit., p. 579.

[3]Honeywell, Op. Cit., p. 6.

[4]Ibid., p. 2.

[5]Vagners and Mar, Op. Cit., p. 584.

[6]Ibid., p. 580.

[7]Ibid., pp. 588-590, and Honeywell, Op. Cit., pp. 9-12.

[8]G.T.A. May, "A Method for Predicting the Number of Near Mid-Air Collisions in a Defined Airspace," The Journal of the Institute of Navigation, Vol. 24, No. 2, April, 1971, p. 205.

[9]Computer Sciences Corporation, Vessel Traffic System Issue Study, Vol. III, Contract No. DOT-CG-22870-A, March 1973, p. C-6.

[10]Ibid., p. C-7.

[11]Ibid., p. C-8.

[12]May, Op. Cit., pp. 207-8, 216-7.

[13]Computer Sciences, Op. Cit., p. C-8.

[14]Yahei Fujii and Reijiro Shiobara, "The Analysis of Traffic Accidents," The Journal of the Institute of Navigation, Vol. 24, No. 4, October, 1971, p. 534.

[15]Yahei Fujii and Kenichi Tanaka, "Traffic Capacity," The Journal of the Institute of Navigation, Vol. 24, No. 4, October, 1971, p. 548.

[16]Ibid., pp. 544-5.

[17]Ibid., p. 548.

[18]*Ibid*., pp. 549-550.

[19]*Ibid*., p. 550.

[20]*Ibid*.

[21]*Ibid*., p. 551.

[22]*Ibid*.

[23]*Ibid*.

[24]*Ibid*.

[25]Fujii and Shiobzra, *Op*. *Cit*., p. 536.

[26]*Ibid*., p. 538.

[27]*Ibid*.

[28]*Ibid*., p. 539.

[29]*Ibid*.

[30]*Ibid*.

[31]*Ibid*., pp. 542-3.

Chapter 5

APPLICATION OF THE ENCOUNTER RATE MODEL TO VESSEL TRAFFIC IN A SPECIFIC WATERWAY

SIGNIFICANCE OF THE MODEL

The modelling techniques developed in the previous pages can be a useful tool in determining the number of encounters in a given segment of the Puget Sound region. Similar modelling techniques have been utilized in the design and analysis of air traffic control systems to assist in evaluation the effects of changes in a particular routing and control structure in a given air space. The development of routing and control procedures take into account the level of risk associated with any particular route structure.

Furthermore, the encounter modelling techniques can provide a means of measuring the effectiveness of various levels of control. G.T.A. May provides an analysis of the measure of effectiveness based on a reorganization of Swedish airspace, which provides figures of merit for various control schemes measured by the reduction in the ratio of the number of collisions to the number of encounters. The United States Coast Guard Study Report further recognizes this approach as a significant method to evaluate the effectiveness of Vessel Traffic Control Systems.

The application of the encounter rate model to existing traffic conditions in Puget Sound would provide the following

advantages to Vessel Traffic Control development:

(1) The areas of Puget Sound where the number of encounters is high could be identified. By assigning an encounter number, or collision probability, to specific areas, those regions which are most in need of increased levels of traffic management, surveillance, or route structure change could be found.

(2) The effectiveness of the existing VTS Traffic Management program could be determined. Estimates of the impact of the initiation of the Bridge-to-Bridge Radio Telephone Act, the achievements of the Puget Sound Vessel Traffic Management Center, and the effectiveness of the Traffic Separation Scheme (TSS) could be determined by noting the reduction in encounters, and the reductions in the number of collisions per encounter since the inception of these programs.

With these goals identified as the hoped-for results of the model, the next logical step is the application of the modelling techniques to specific regions of Puget Sound.

TRAFFIC PATTERNS IN ADMIRALTY INLET

The Traffic Separation Scheme

The Puget Sound VTS Traffic Separation Scheme consists of a series of one-way traffic lanes 1,000 yards wide, separated by a 500 yard wide traffic separation zone. The traffic lanes merge at precautionary areas which are 5,000 yards in diameter. Generally speaking, the regulations regarding participation in the system state that certain classes of

vessels transiting the area are required to participate in the VTS, while others may participate on a voluntary basis. Regulations currently under consideration by the United States Coast Guard will require mandatory participation in the VTS by a very broad range of vessels.[1] In actual fact, the participation in the VTS has been increasing since its inception, and the level of voluntary participation during the period since September of 1973 approximates the mandatory participation level. For the purposes of this model, it will be assumed that the level of mandatory participation is 100 percent of the four classes of vessels under consideration.

A sector of the chart (C & GS 6401) covering Admiralty Inlet, and depicting the basic Traffic Separation Scheme is presented on the following page. One should note that the Traffic Separation Scheme has been modified slightly since the initiating regulations were established in 1972. These alterations have included minor shifts in a segment of the Traffic Lanes between Bush Point and Pilot Point, and the addition of several more buoys in the system from Bush Point south. The additional buoys, and the resultant re-naming of the existing buoys are not represented in this study. Neither, for that matter, is the shift in the traffic lanes, which was accomplished to minimize occasional conflicts between transiting traffic and commercial fishing boats during certain periods of the year. While recognizing that these changes have occurred, their impact on the calculations of encounter rates was considered to be negligible in this study, and the

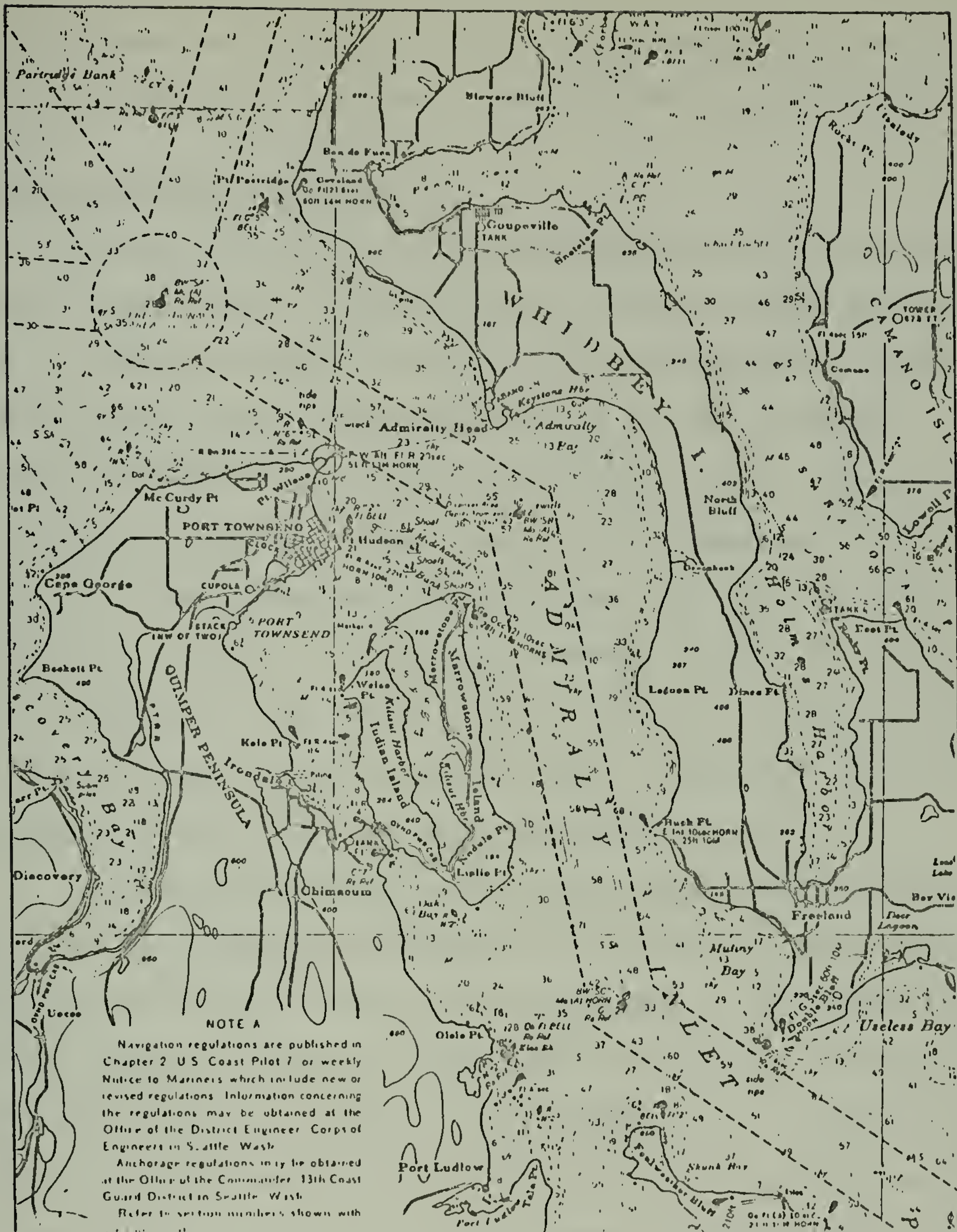

Figure 5-1

Segment of the Traffic Separation Scheme Within Admiralty Inlet

Source: "Admiralty Inlet and Puget Sound," Chart C & GS 6401.

traffic lanes and buoy locations as originally developed for Puget Sound will be utilized in all further calculations.

Modelling Traffic Patterns

Accurate data on vessel track history within the waterways of Puget Sound does not exist. Data on vessel movements, such as those obtained by the previously mentioned technique of Programmed Radar Photography, would aid in defining frequently-transitted paths, and thereby greatly reduce the uncertainty in encounter rate modelling. Yamaguchi and Sakaki cite the importance of this track history in traffic regulation. Figure 5-2 displays a sample of the findings of one such study of the Uraga Strait in Japan. The distribution of vessel tracks and density is clearly displayed, as are the effects on traffic flow of several obstructions.[2]

Lacking exact data such as that obtained by sophisticated traffic analysis techniques, it is hoped that reasonable estimates of traffic flow can be developed. The estimates of traffic patterns used in the Honeywell study were assumed to be of uniform density, randomly distributed across as effective navigable channel width of five miles. However, present information indicates that the bulk of vessel traffic follows the VTS Traffic Separation Scheme. In general, it has been reported by Coast Guard Officials and by Puget Sound Pilots that deep-draft vessels (freighters and tankers) adhere to the existing traffic lanes. Shallow draft vessels usually travel to the right of existing lanes, generally out of the way of larger, faster deep draft vessels. Towing boats with barges

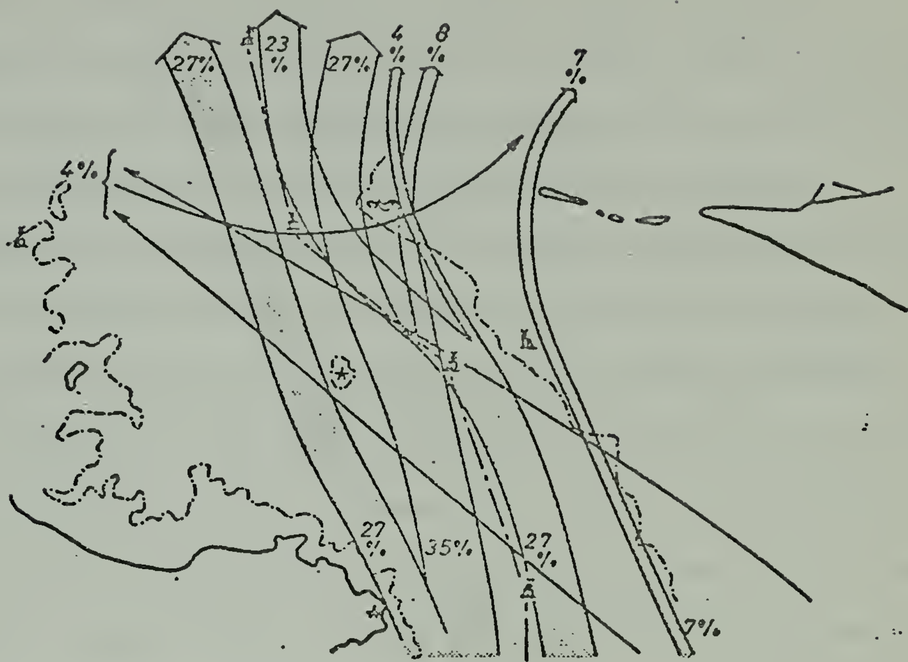

Figure 5-2

Tracks of Small Northward-Bound Vessels in Uraga Strait

Source: Yamaguchi and Sakaki, "Studies in Marine Traffic Engineering."

will often stay close to the shore, well clear of the traffic lanes, in an attempt to avoid stronger tidal current. Frequently, however, tow boats in the Vessel Traffic System will cross the traffic lanes and proceed against the flow of traffic to take advantage of a more favorable tidal current.

Based on descriptions of traffic patterns provided by those most familiar with the region, as well as limited personal observation, assumptions will be made regarding "typical" traffic conditions for Admiralty Inlet, and the remainder of Puget Sound in general. First, the majority of the deep draft vessels remain within the one way 1,000 yard wide traffic lanes. Few vessels navigating Puget Sound rely on precise navigation and piloting practices, as few obstructions or restrictions exist. Coupled with the fact that the Puget Sound region has a relatively low traffic density and the fact that the traffic lanes themselves are not well defined, vessels generally are not restricted by the traffic lanes, and frequently stray outside of them. Secondly, the majority of Tow Boat traffic follows the general traffic separation scheme, but usually proceeds near the outside boundary of the traffic lane. Thirdly, tow boats occasionally cross the traffic lanes, and proceed against the flow of traffic, but well outside of the traffic lanes. Finally, no vessels utilize the 500 yard wide precautionary area between the traffic lanes, except while crossing the lanes.

Based on these previous points, the conditions of traffic flow to be modelled will assume that vessels are

travelling as one directional streams of uniform density through a waterway with an effective width of 1,500 yards (three quarters of a nautical mile). Most areas of Admiralty Inlet are considerably wider, but it will be assumed that the 1,500 yard width will compensate for the probable head-on encounters which occasionally will exist close to shore. Further, the restrictions in the one-way lanes at some points are approximately 1,500 yards, taking into account the fact that prudent mariners will not approach closer than one quarter mile (500 yards) to the shore, or shoal water.

TRAFFIC DENSITY IN ADMIRALTY INLET

From the data presented in the United States Coast Guard Vessel Traffic Survey of June 1973 it was determined that there were 1,127 vessel transits between Buoy "SA" (the precautionary area north of McCurdy Point) and Buoy "SC" (off Mutiny Bay). Assuming an equal number of vessel transits occurred in the northerly and southerly direction, the number of vessels of each class which made up the one-way traffic in the waterway are listed on the following page.

Index numbers were previously developed to correct the June 1973 statistics in order to depict traffic volume in the base month of April 1974. If traffic density within Puget Sound varies linearly over periods of time, then the April volume may be approximated by multiplying June statistics by the index numbers. Assuming this to be a valid statement,

Table 5-1

Vessel Transits for Admiralty Inlet
(June 1973)

	Both Directions	One-Way
Freighters	295	147.5
Tankers	34	17
Tow Boats	640	320
Miscellaneous	158	79
Totals	1,127	563.5

the approximate traffic flow during April 1974 through Admiralty Inlet is presented in the following table.

Table 5-2

Estimated Vessel Traffic for Admiralty Inlet
(April 1974)

	Both Directions	One-Way
Freighters	295.	147.5
Tankers	44.2	22.1
Tow Boats	704.	352.
Miscellaneous	126.4	63.2
Totals	1,169.6	584.8

As was described previously, the results of a traffic survey conducted to determine characteristics of vessel traffic within Puget Sound showed an hourly variation in traffic

density during the week. It was determined that during 85 hours of the week 58 percent of the total weekly vessel traffic occurred. This relationship will be assumed valid for the month of April 1974, and it will furthermore be assumed that this relationship is valid for all classes of vessels, and in all areas of the Puget Sound region. Separate densities can then be established for two periods of time. The month can be divided into two equal parts, in which traffic flow, Q_i, will equal 57 percent (for i = 1, the period of higher density), and 43 percent (for i = 2, the period of lower density).

A general expression for Total Traffic Volume, Q_{total}, would be:

$$Q_{total} = \sum_{i=1}^{n} Q_i \qquad (i = 1, 2, \ldots n) \qquad (18)$$

where Q_i = vessel transits during a particular period of time.

The values of traffic volume, Q, for the month of April are listed on the following page.

The mean vessel density, ρ , can be calculated from equation (5) when traffic volume, Q, mean transit speed, $\bar{V}$, and the width of the waterway, w, are known. The general expression for the traffic density at a particular time (i) and of a particular vessel class (j) is:

$$\rho_{ij} = Q_{ij} \;/\; \bar{V}_j \;\; w \qquad (19)$$

where i = 1 for a period of high density

2 for a period of low density

j = F for Freighters, T for Tankers,

TB for Tow Boats, and M for

Miscellaneous Vessels

Table 5-3

Estimated One-Way Traffic Volume for Admiralty Inlet
(April 1974)

	(High Density Period)(57%)	(Low Density Period)(43%)
Freighters	84.0	63.4
Tankers	12.6	9.5
Tow Boats	200.6	151.4
Miscellaneous	36.0	27.2
Totals	333.2	251.5

The average traffic density (vessels per square mile) for all classes of vessels in Admiralty Inlet is computed from the information previously developed in preceeding tables. The values were computed from equation (19):

$$\rho_{ij} = Q_{ij} \;/\; 360 \;\; \bar{V}_j \;\; w$$

where Q_{ij} = traffic volume in vessels per month for the ith time period for the jth class of vessel

$\bar{V}_j$ = mean velocity for the jth class of vessel (from Table 2-4)

w = 0.75 nautical miles

360 = the number of hours in 50 percent of a month.

Table 5-4

Computed Vessel Density For One-Way Traffic in Admiralty Inlet (Vessels of Class j Per Square Mile)

j (Vessel Class)	i (Time Period)	
	1 (High Density)	2 (Low Density)
F	.020	.015
T	.004	.003
TB	.103	.080
M	.012	.009

The total traffic density, $\rho_{(total)}$, for the ith time in Admiralty Inlet is the sum of the ith densities, or

$$\rho_{i\ (total)} = \sum_j \rho_{ij} \tag{20}$$

for j = (F,T,TB,M) and i = (1,2)

For the period of high volume (i = 1), the total vessel density is 0.139 vessels per square mile in the one-way channel. For periods of low traffic volume, (i = 2), the total vessel density is 0.107 vessels per square mile.

COMPUTATION OF THE ENCOUNTER RATE FOR THE CO-DIRECTIONAL CASE

The formula for the encounter rate and number of encounters per unit area, equations (8) and (9) was developed previously. The number of encounters per unit area of a waterway, E, is:

$$E_{12} = \bar{V}_R \ D \rho_1 \rho_2 \ T \tag{8}$$

where ρ_1 and ρ_2 are the densities of respective groups of vessels. The number of encounters within a single group of vessels was developed to be:

$$E_{11} = \tfrac{1}{2} \bar{V}_R \ D \ \rho_1^{\ 2} \ T \tag{9}$$

encounters per unit area.

Relative Velocity

The relative velocity for groups of vessels moving along the same route was previously assumed to be $|V_1 - V_2|$, except in the case of encounters between members of the same group, where $\bar{V}_R$ will be the standard deviation of the speeds. The following table summarizes the relative velocities between the four classes of vessels moving at their mean speed within a stream, $\bar{V}_{Rjk}$, based upon the values for mean speed as determined from a two-week survey of vessel traffic (p. 85).

Size of the Effective Domain

As previously stated, the size of the psychological boundary called the effective domain, which surrounds a vessel and into which another vessel will choose not to intrude, is a

Table 5-5

Relative Velocity Between Vessels For
Co-Directional Encounters
(Speed in Knots)

V_{Rjk} / Vessel Class (j)	Vessel Class (k) F	T	TB	M
F	3.0	2.1	8.4	4.5
T		2.0	6.3	2.4
TB			2.6	2.9
M				3.5

function of vessel length. The shape of the effective domain was determined to be an ellipse, with a semi-axis minor of approximately 3L. Furthermore, the size of the effective domain in crossing and anti-directional encounters was estimated to be 4L.

To simplify computational techniques, the size of the effective domain will be assumed to be 4L for all cases of crossing, meeting, and overtaking. While this somewhat reduces the area of encounter in the co-directional case, the loss will be assumed to be minimal. In fact, the change in shape of the area, from elliptical to circular, will increase the size of effective domain in passing situations. A comparison of the change in shape is depicted in Figure 5-3. Proceeding on the assumption that the effective domain of a vessel approximates a

circle of radius 4L, the special case of Towing Boats must be examined in greater detail.

Figure 5-3 represents the effective domain of the tug and barge combination which will be considered as the average for the Puget Sound waterways. The overall length of tug and barge is 1,100 ft., and consists of a 100 ft. tow boat, 300 ft. barge, and 700 ft. of towing cable. In the co-directional encounters, the tug and barge combination will assume to exhibit an effective domain of 4L, where L = 300 ft., the length of the barge. The size of the effective domain of the barge is therefore assumed to be the significant factor in determining the overall effective domain of the Tow Boat train.

The size of the effective domain between vessels of dissimilar length was assumed to be 4L'. The characteristic length between vessels of dissimilar class, L', (or L_{jk}) have been determined from the mean length of the different classes, utilizing equation (14) previously presented by Fujii.

$$L_{jk} = ((L_j^{\ 2} + L_k^{\ 2}) \ / \ 2)^{\frac{1}{2}} \tag{14}$$

where (j,k = F,T,TB,M). The computations are summarized in Table 5-6 (See p. 88).

Fujii stated that the frequency of encounters, E, could be computed from equations (8) and (9) by assuming that D is equal to the diameter of the effective domain, $8L_{jk}$.[3] Therefore, the evasion diameter, D_{jk} is equal to $8L_{jk}$. Values for the evasion diameters have been computed in Table 5-7 for encounters between the various classes (See p. 88).

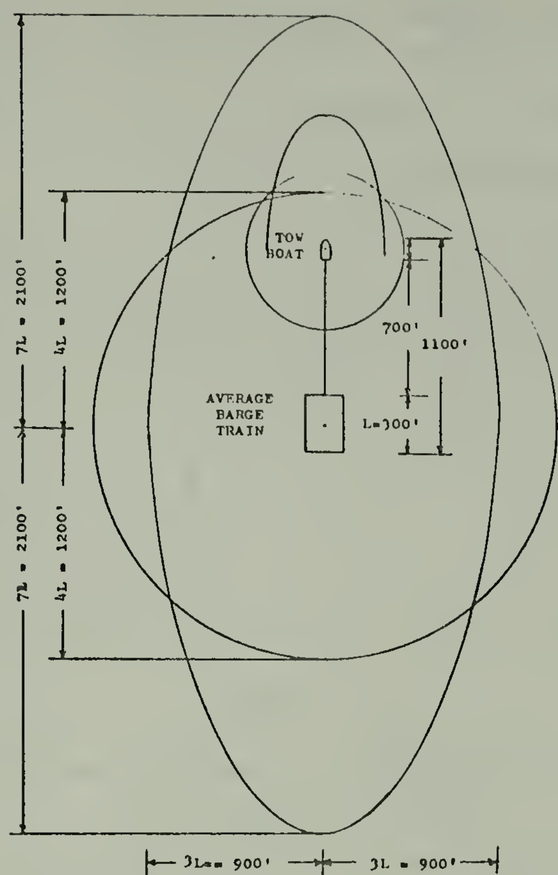

Figure 5-3

Effective Domain of a Tug and Barge Combination

Comparison of the relative size of the evasion diameter for an estimated average size tow and barge combination. Circular domain R = 4L. Elliptical domain r = 7L, s = 3L.

Table 5-6

Computed Values of Characteristic Length, L_{jk}, For Effective Domain (Characteristic Length in Feet)

Vessel Class (j)	Vessel Class (k)			
	F	T	TB	M
F	480	530	400	350
T		580	460	420
TB			300	230
M				140

Table 5-7

Computed Values of Evasion Diameter D_{jk} (D_{jk} in Feet and Nautical Miles)

Vessel Class (j)	Vessel Class (k)			
	F	T	TB	M
F	3,840 (.64)	4,240 (.71)	3,200 (.53)	2,900 (.47)
T		4,640 (.77)	3,680 (.61)	3,360 (.56)
TB			2,400 (.40)	1,840 (.31)
M				1,120 (.19)

Encounter Rate Computations

The number of encounters in a one-way waterway during a time period is:

$$E_{total} = \sum_i \sum_j \sum_k E_{ijk} \quad A \tag{21}$$

where E_{ijk} is the number of encounters per unit area between the various j and k classes of vessels, in each i time period, and A is the area of the waterway.

$$E_{ijk} = \tfrac{1}{2} \bar{V}_{Rjk} D_{jk} \rho_{ij}^{2} \qquad \text{(where } j = k\text{)} \tag{22}$$

$$E_{ijk} = \bar{V}_{Rjk} D_{jk} \rho_{ij} \rho_{ik} \qquad \text{(where } j \neq k\text{)} \tag{23}$$

and where j and k designate the vessel class (j,k = F,T,TB,M).

Utilizing the values of Tables 5-4, 5-5, and 5-7, and equations (24) and (25), the number of encounters per unit area of the one-way effective waterway through Admiralty Inlet has been computed for all encounters E_{jk}, during the two periods of traffic density (See Tables 5-8 and 5-9, p. 90).

If the number of collisions between vessels is proportional to the number of encounters, then the probability of collisions between various classes of vessels could be determined from the previous two tables. Assuming this to be correct, the probability of a collision between tow boats and freighters, or between two tow boats, is significantly higher than, for example, the probability of a collision between two tankers or two miscellaneous vessels. The probability of a collision between a freighter and tow boat is approximately

Table 5-8

Encounters Per Unit Area in Admiralty Inlet During Periods of High Traffic Volume (Co-Directional Encounters Per Unit Area (10^{-4}) Between the j and k Classes of Vessels Within the Traffic Lanes During April 1974, for i = 1)

E_{ijk} (10^{-4})	j Class of Vessels			
k Class of Vessels	F	T	TB	M
F	3.84	1.19	91.7	5.08
T		0.12	15.8	0.65
TB			55.2	11.1
M				0.48

Table 5-9

Encounter Per Unit Area in Admiralty Inlet During Periods of Low Traffic Volume (Co-Directional Encounters Per Unit Area (10^{-4}) Between the j and k Classes of Vessels Within the Traffic Lanes During April 1974, for i = 2)

E_{ijk} (10^{-4})	j Class of Vessels			
k Class of Vessels	F	T	TB	M
F	2.16	0.67	53.4	2.86
T		0.07	9.22	0.36
TB			33.3	6.47
M				0.27

1,000 times more likely to occur than collisions between two tankers, assuming all of the previously developed conditions are valid.

The number of total encounters per unit time per square mile, E_{ijk}, in each of the one-way traffic lanes of Admiralty Inlet was found by summing the values of Tables 5-8 and 5-9. The total number of encounters within the traffic lanes of Admiralty Inlet for April 1974 can be estimated by multiplying the encounters per square mile by the area of the traffic lanes. The length of the traffic lanes between buoy "SC" and the precautionary area surrounding buoy "SA" is about 16 miles. Each effective traffic lane was assumed to be 0.75 miles wide, and there are two lanes. The total area of the Admiralty Inlet lanes is:

$$A_1 = 2\ lw = 24 \text{ square miles.}$$

The total estimated number of co-directional encounters in the traffic lanes of Admiralty Inlet during April 1974 was therefore:

$$(E_{1jk} + E_{2jk})\ A_1 T = 254 \text{ co-directional encounters per month.}$$

COMPUTATION OF THE ENCOUNTER RATE FOR TRAFFIC INTERSECTIONS

Size of the Encounter Area

The choice of the size of the traffic intersection and encounter areas will depend upon the geography of the intersection area and an estimate of vessel tracks within the area. The modelling technique presented in this study does not attempt to estimate encounter rates within the confines of a

harbor. Traffic patterns within a harbor are complex, and vessels proceed at slow speed. If this encounter rate model is to be valid, the areas of traffic intersections or approaches to harbors must be selected so that vessel traffic still generally approximates a stream of vessels moving in the same direction. Furthermore, the stream must also meet certain criteria regarding vessel speed. The length of the intersection areas were chosen such that it was assumed vessels would be operating at speeds greater than one half their normal transit speed. No attempt was made in this study to simulate complex vessel movements in harbor areas or in areas where it was estimated that vessels maneuvered at very slow speed. The encounter rate was estimated only in those situations in which vessels are transitting at speeds greater than one half their normal transit speed. Encounter rates were therefore identified for situations which produced potential "true collisions," which are defined as collisions in which both vessels are proceeding at more than one half their normal transit speed.[4]

Crossing Encounters in Admiralty Inlet

Having previously estimated the number of encounters in a waterway for streams of vessels moving in the same direction, it becomes necessary to estimate encounters which occur as a result of vessels entering or departing the lanes. The Puget Sound VTS Traffic Survey of June 1973 provided totals for vessels whose destination was Port Townsend.

Vessels heading north through Admiralty Inlet must eventually cross the south bound traffic lane to reach their destination, Port Townsend. Also, vessels departing Port Townsend must pass through a stream of vessels bound for the Port. The number of arrivals and departures at Port Townsend during the month of June 1973 is listed below.

	June 1973	April 1974
Freighters	4	4
Tow Boats	208	228

Vessels Bound From/To Port Townsend

Figure 5-4 represents an attempt to model the traffic patterns for the entrance to Port Townsend, using June 1973 traffic totals indexed to represent April 1974 traffic estimates.

It is again noted that the previous attempts to model the traffic intersection at Port Townsend (Figure 5-4) is a very crude approximation. This assumes that no conflicts are presented by vessels weaving from the outside to the inside of the traffic lane in preparation for their turn. The conflicts presented in this weaving will be assumed to be compensated for by the reduced traffic density in the main stream between points A and B. A further assumption is that vessels can easily merge into a traffic lane without presenting an encounter situation to vessels within the lane. These assumptions may be correct if the density of the traffic is

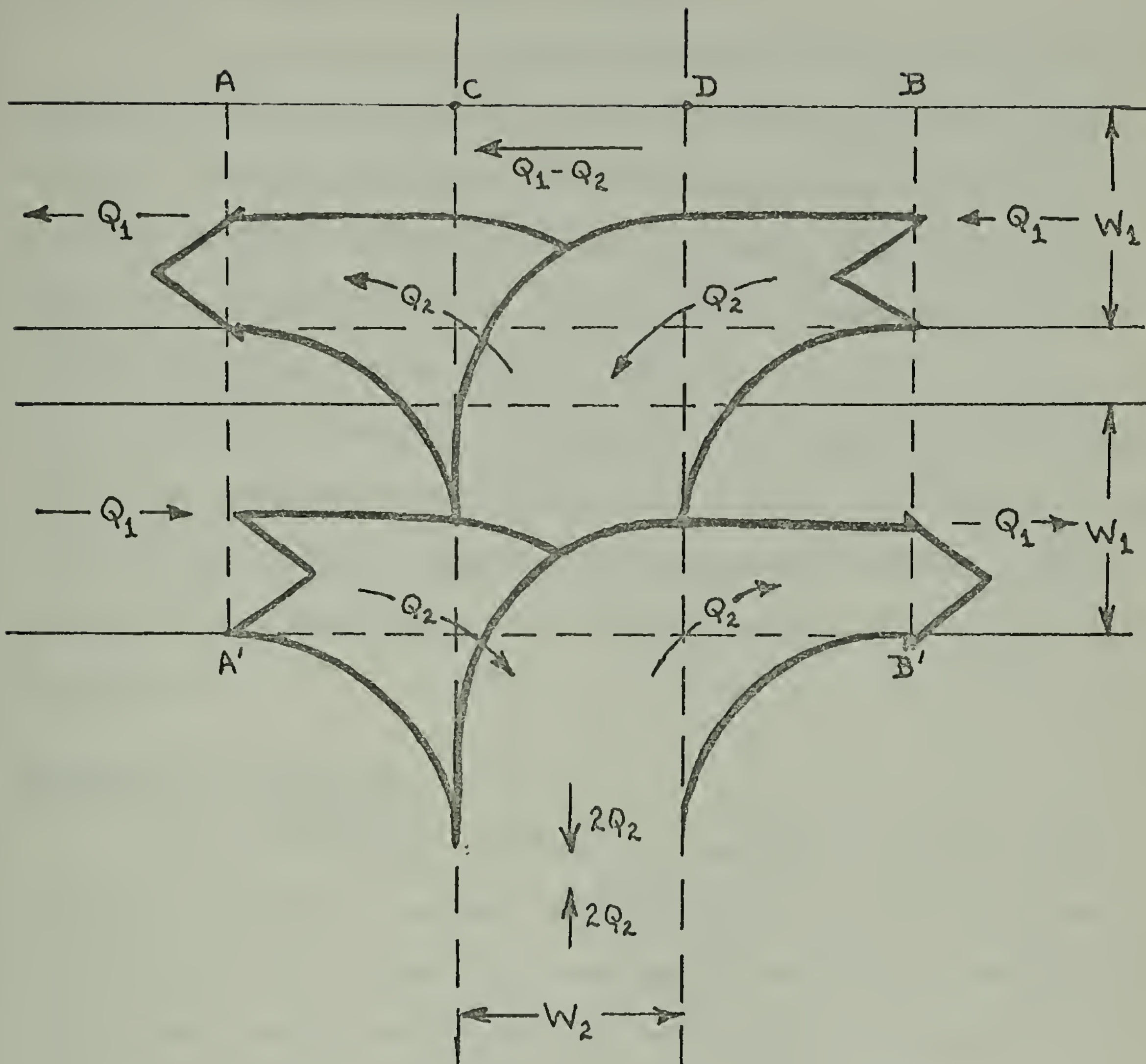

Figure 5-4

Estimated Traffic Patterns in a Traffic Intersection

relatively low, and if there is sufficient navigating area outside the lanes to merge gradually.

If the previous assumptions are in fact valid, and Figure 5-4 does represent the Port Townsend traffic intersection, the calculations of encounters in the intersection (or any similar intersection) may be made from Figure 5-5, which is a simplification of the traffic intersection described by the previous figure (Figure 5-4).

If the previous assumptions are valid, then the total number of encounters resulting from vessels entering or leaving the traffic lanes, a Traffic Intersection Situation, may be estimated by computing the encounters within area A_1 and A_2 of Figure 5-5.

Encounters in Area A_1

The encounters in area A_1, bounded by points CDEF, consist of head-on (or anti-directional) encounters between two streams of equal volume Q_2, overtaking encounters between the two groups, and crossing encounters between the main body stream of volume Q_1 and the two crossing streams.

The encounters in area A_2, bounded by points EFGH, consist of anti-directional encounters between two steams of volume 2 Q_2, and overtaking encounters within the streams.

It is therefore necessary to estimate a value for w_2 and l_2 the length and width of the effective waterway entering the traffic intersection. The choice of these dimensions could best be made by an analysis of actual vessel track history. Lacking this type of detailed analysis, it will be assumed that

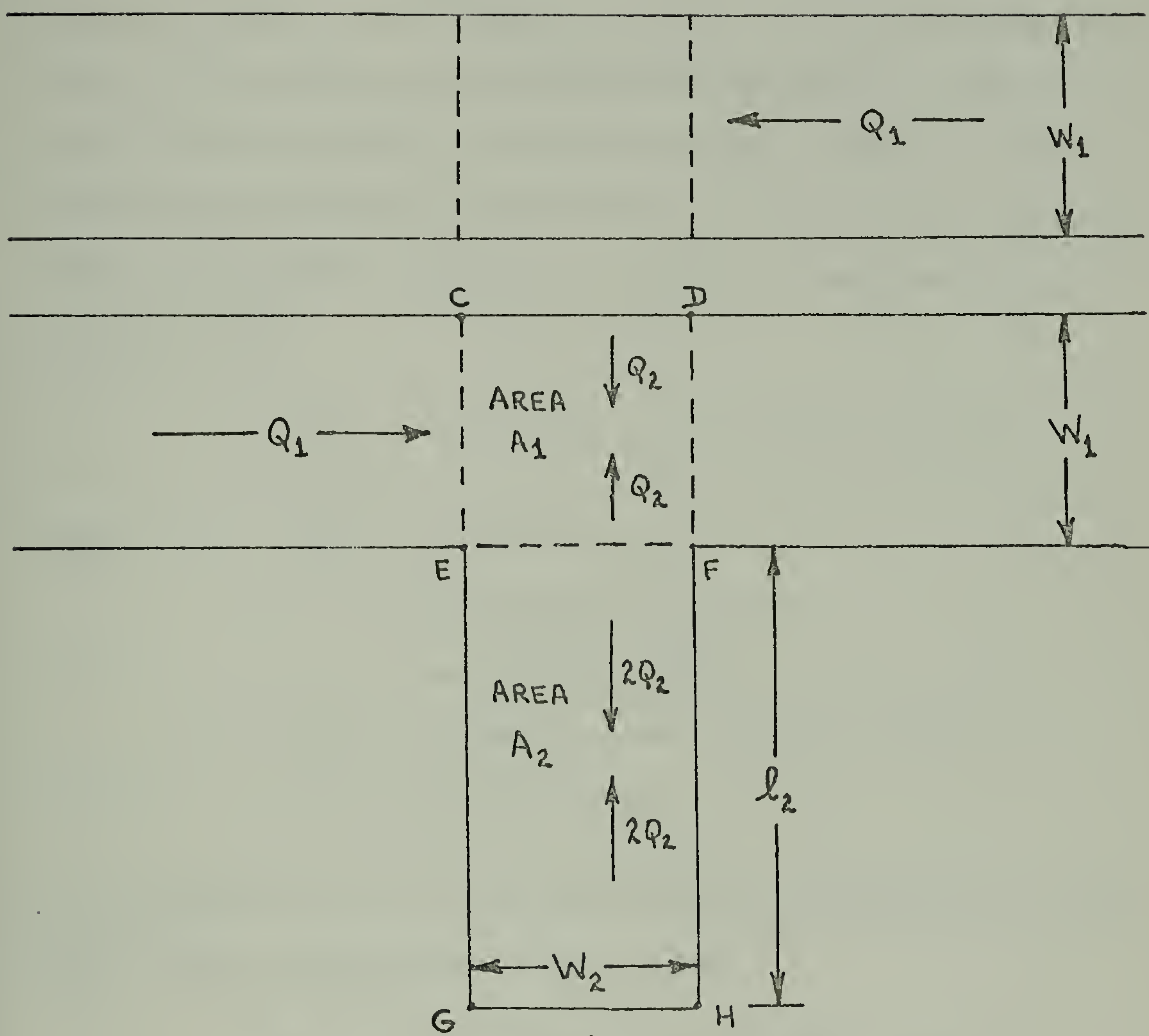

Figure 5-5

Simplified Estimated Traffic Patterns
In a Traffic Intersection

the dimensions of l_2 = one nautical mile and w_2 = one nautical mile approximates the size of the intersecting traffic lane. Therefore, Q_2 can be computed from information obtained from the Coast Guard June Traffic Survey. If it is assumed that the number of vessels that entered Port Townsend are equal to the number which departed, and that an equal number of these vessels were northwest and southeast bound through Admiralty Inlet, the traffic density, ρ_2, can be computed from equation (19):

$$\rho_{12} = (\tfrac{1}{4}) \quad \rho_{ij} = (Q_{ij}/360\ \bar{V}_j\ w)\ (\tfrac{1}{4})$$

where

Q_{ij} = (.57)(228) for i = 1
= (.43)(228) for i = 2

w = one nautical mile

$\bar{V}_j$ = 7.2 knots, the average tow boat transit speed.

From equation (19), the estimated tow boat density for the traffic lane intersection, ρ_{i2}, is:

ρ_{i2} = .0125 vessels per square mile for i = 1, and
= .0095 vessels per square mile for i = 2.

The number of co-directional encounters per unit area within the streams in area A_1 is computed from equation (22):

$$E_{ijk} = \tfrac{1}{2}\ \bar{V}_{Rjk}\ D_{jk}\ \rho_{ij}^{\,2}\ T$$

where $\bar{V}_{Rjk}$ = 2.6 knots, the standard deviation of the average tow boat speed.

D_{jk} = 0.40 nautical miles.

For (i = 1), ρ_{ij} = (.0125), and T = 360 hours in 50 percent of a month, the number of co-directional encounters per stream per square mile of area A_1 is:

$$E_{1jk} = (.029)$$

$$E_{2jk} = (.017)$$

The total encounters between the two streams in an area of (.75) square miles in:

$$E_{ijk}\ (2)(A_1) = (.046)(2)(.75)$$

$$= (.07) \text{ encounters per month}$$

The number of anti-directional encounters can be computed from equation (23):

$$E_{ijk} = \bar{V}_{Rjk}\ D_{jk}\ \rho_{ij}\ \rho_{ik}\ T$$

where i = 1 for time period 1

2 for time period 2

$\bar{V}_{Rjk} = \bar{V}_{TB} + \bar{V}_{TB}$ = 14.4 kts.

$\rho_{1j} = \rho_{1k}$ = (.0125) vessels per square mile

$\rho_{2j} = \rho_{2k}$ = (.0095) vessels per square mile

A_1 = (.75) square miles

T = 360 hours in 50 percent of a month.

The number of anti-directional encounters within area A_1 was computed to be approximately (.4) encounters per month.

The number of encounters per unit area which result from the Port Townsend-generated traffic grossing the normal traffic lane can be determined from equation (23):

$$E_{ijk} = \bar{V}_{Rjk} D_{Rjk} \rho_{ij} \rho_{ik}{}^{T}$$

where ρ_{ij} = density of the main stream during time period i for vessel classes (j = F,T,TB,M)

ρ_{ik} = two times the density of ρ_{i2}, or (.025) for i = 1, and (.019) for i = 2

D_{Rjk} = the relative collision diameter, $4L_{jk}$ (from Table 5-7)

T = 360 hours in 50 percent of a month for i = (1,2)

$\bar{V}_{Rjk}$ = the relative velocity in a crossing encounter,

$$\bar{V}_{Rjk} = \sqrt{V_j{}^2 + V_k{}^2 - 2V_jV_k \cos\theta}$$

As previously mentioned, the crossing encounter was assumed to be at right angles to the traffic lane. (The regulations governing the conduct of vessels crossing traffic lanes state that lanes will be crossed perpendicularly.)[5] Table 5-10 presents the relative velocity for encounters between the various classes of vessels for a crossing angle of 90°.

Table 5-10

Relative Velocity for Encounters Between Vessels Crossing at an Angle of 90 Degrees (Velocity in Knots)

$\bar{V}_{Rjk}$	Vessel Class j			
Vessel Class k	F	T	TB	M
F	22	21	17	19
T		19	15	17
TB			10	13
M				16

Table 5-11

Computed Values for Crossing Encounters, E_{ijk}, in Area A_1 of Admiralty Inlet (Encounters Per Square Mile)

Vessel Class		E_{ijk}	
j	k	i = 1	i = 2
F	TB	1.62	.94
T	TB	.32	.18
TB	TB	3.71	2.20
M	TB	.25	.14

Utilizing the previously presented data from Tables 5-7 and 5-10, and equation (23), the number of crossing encounters per square mile, E_{ijk}, in area A_1 have been tabulated for the two streams of j and k vessels (Table 5-11).

The number of crossing encounters within area A_1 is computed below:

$$\sum_i \sum_j \sum_k E_{ijk} A_1 = (9.4)(.75) = 7 \text{ encounters per month}$$

Therefore, the total number of encounters within area A_1 is:

Co-Directional	0.07
Anti-Directional	0.4
Crossing	7.0
Total Estimated Encounters in Area A_1	8

Encounters in Area A_2

Encounters in area A_2 can be computed in the same manner as the co- and anti-directional encounters in area A_1, but with vessel densities twice as large as in area A_1.

Co-directional encounters per unit area are:

$$E_{ijk} = 0.18 \text{ for } i = 1$$
$$= 0.07 \text{ for } i = 2$$

Anti-directional encounters per unit area are:

$$E_{ijk} = 1.30 \text{ for } i = 1$$
$$= .75 \text{ for } i = 2$$

The sum of the co- and anti-directional encounters per unit area is 2.30 encounters per square mile. The size of area A_2 is one square mile, so the total number of encounters estimated to occur during the month of April is less than 3.0 encounters.

Other Traffic in the Intersection

Other traffic in the Port Townsend area which crossed the traffic lanes consisted of a total of four Freighter transits and Washington State Ferry traffic. The encounters involving these vessels were determined in the manner of a single vessel crossing a traffic lane, and passing through area A_1 and A_2.

The number of encounters resulting from a single intruding vessel (k) crossing a stream of vessels of density ρ_{ij} was estimated using equation (7):

$$E_{ijk} = \bar{V}_{Rjk} \ D_{Rjk} \ \rho_{ij} \ T \tag{24}$$

Utilizing the previously computed values for the traffic density of the one-way traffic lane, ρ_{ij}, it was necessary to assume a value for $\bar{V}_k$, which will be used in computing $\bar{V}_{Rjk}$, the relative velocity, and T, the time for a vessel to cross the traffic lane at velocity $\bar{V}_k$. It was estimated that freighters, entering the approaches to Port Townsend, are travelling at something less than their normal average transit speed, $\bar{V}_F$. Vessels entering port must reduce speed in preparation for landing, and vessels getting underway have not yet reached their

normal sea speed when crossing the lanes. The crossing velocity, $\bar{V}_k$, was estimated to be ten knots for freighters, and also ten knots for the Port Townsend Ferry. From this estimated speed, the time T during which an intruding vessel is within the effective traffic lane .75 miles in width is approximately 1/10 of an hour.

The evasion diameter, D_R, has been computed for encounters between freighters and other class of vessels. The length of the ferry Olympic, which was the vessel assigned to this route during April 1974 is 207 feet overall.[6] The length between perpendiculars was assumed to be 200 feet, and the evasion diameter was computed in a manner similar to that of Table 5-7.

The values for $\bar{V}_{Rjk}$ and D_{Rjk} have been tabulated in Table 5-12 (See p. 104) for a single vessel crossing the traffic lanes at a speed of ten knots.

Utilizing the data from Table 5-12 and equation (24), the number of encounters per lane crossed by an intruding vessel, E_{ijk}, in Admiralty Inlet is presented on page 104.

From the previous computations, a freighter crossing a traffic lane to enter Port Townsend is likely to encounter (0.10) vessels per lane crossing during periods of high traffic volume. A ferry crossing a single traffic lane was estimated to have encountered (.07) vessels per lane crossed. The four freighters would add less than one encounter to the area totals over the month of April 1974. The ferry, however, makes

Table 5-12

Computed Values for a Vessel Crossing a Stream of Vessels

Vessel Class	Evasion Diameter, $D_R jk$ (Nautical Miles)		Relative Velocity, $\bar{V}_{Rjk}$ (Knots)
j	Vessel Class k = F	Vessel Class k = 200 ft.	$\bar{V}_k$ = 10 kts
F	.64	.50	18
T	.71	.58	17
TB	.53	.34	12
M	.47	.23	15

i	j	E_{1jk}	i	j	E_{1jk}
F	F	.020	Ferry	F	.018
F	T	.005	"	T	.004
F	TB	.066	"	TB	.042
F	M	.008	"	M	.004
	E_{ijk} =	.10			.07

12 one-way crossings per day, at two lanes per crossing, and will add to the totals 50 encounters per month.

The freighter and ferry traffic also pass through areas A_1 and A_2, and it is estimated that they will encounter the streams of tow boat traffic as co- and anti-directional encounters. Again utilizing equation (24), with the values for D_{Rjk} computed previously, and a relative speed of $\left|\bar{V}_j - \bar{V}_k\right|$,

the number of encounters were estimated. To facilitate computations, a uniform high density will be assumed, and area A_1 and A_2 will be combined. Transit time, T, require to traverse this area is approximately 2/10 hour. Relative velocity, $\bar{V}_{Rjk}$ is 17.2 knots for anti-directional, and 2.8 knots for co-directional encounters. The number of encounters per transit is tabulated below.

Vessel Class i	j	E_{ijk} (Encounters Per Transit) Co-Directional	Anti-Directional
F	TB	.007	.045
Ferry	TB	.005	.029

The total number of encounters which result from four freighter transits through area A_1 and A_2, 4(.052), is less than one per month. The total number of encounters resulting from 12 daily ferry transits is 12.3 encounters per month.

Summary of Vessel Encounter Rates In Admiralty Inlet

A summary of estimated vessel encounters within Admiralty Inlet indicates that most of the encounters are within the traffic lanes. The encounters estimated to result from ferry traffic is significant, as is that of other traffic crossing the traffic lanes. Few encounters result from co- and anti-directional encounters in the traffic intersection approaches to Port Townsend.

Co- and anti-directional		
within the traffic lanes		254
Intersection traffic		
within area A_1		8
within area A_2	less than	3
Freighter crossing	less than	1
Ferry Crossing		50
Total Encounters Per Month		316

In the following chapter various sectors of the Puget Sound area will be identified. The encounter rates for vessel traffic in these sectors was estimated in the same manner as that the preceeding analysis of encounter rates in this segment of Admiralty Inlet.

FOOTNOTES

[1]"Vessel Traffic Systems, Puget Sound," Federal Register, July 10, 1974, 39 FR 25430-1.

[2]Yamaguchi and Sakaki, "Traffic Surveys in Japan," pp. 521-534.

[3]Fujii and Shiobara, "The Analysis of Traffic Accidents," p. 539.

[4]Ibid., p. 536.

[5]"Puget Sound Vessel Traffic System Notice of Proposed Rulemaking," Federal Register, August 6, 1973, 38 FR 21231.

[6]Washington State Ferries, Ferry Schedule Late Winter-Spring 1974, and Washington State Ferries Fleet 1974 vessel statistics.

Chapter 6

APPLICATION OF THE ENCOUNTER RATE MODEL TO OTHER AREAS OF PUGET SOUND

SIGNIFICANCE OF ENCOUNTER RATE MODELLING

Proceeding on the assumption that encounter rates between vessels can be adequately determined by the encounter rate model, and that traffic volume as presented by the Coast Guard Vessel Traffic Survey correctly reflects vessel traffic, the encounter rates throughout the Puget Sound region can be computed for individual sectors of the waterway. These sectors were arbitrarily chosen on the basis of geographical coherency, and generally coincide with the established boundaries of the Vessel Traffic System. The object of this sectorization is to identify those areas of higher encounter rates, and consequently higher probability of collision. If in fact there is a significantly higher encounter rate in certain areas, these areas may then be the most likely candidates for more sophisticated levels of traffic management. Assuming that the Coast Guard will proceed with its program to provide more advanced navigational assistance and traffic management on a continuing basis, sectors can be identified so that the limited resources available may be utilized to their maximum level of effectiveness.

If the encounter rate model can be used to adequately evaluate the relative risks of collision within various

segments of Puget Sound, it may also provide a means to measure the impact of changes in vessel traffic characteristics. The risks associated with increased vessel activity, and increased sizes of vessels could be determined before these traffic changes were introduced. As an example, the number of encounters caused by increasing the frequency of large bulk petroleum carriers along a specific route could be estimated. Alternative routing schemes could be identified which would limit or minimize the exposure of these types of vessels to collision risks. Furthermore, the overall risk involved in the entire hazardous cargo transfer system could be identified, and a mix of waterborne transfer vessels and routes identified to produce the minimum overall risk to the environment, as well as other traffic. In this respect, the location of a major petroleum offloading facility could take into account collision risk associated with increasing traffic volume of large tankers, as well as smaller tankers and tank barges which might be used for transshipment to other areas. The costs of various types and locations of facilities could therefore take into account projected costs associated with vessel traffic risks.

SECTORIZATION OF PUGET SOUND

The Puget Sound region was divided into nine sectors, based on traffic patterns identified by the Puget Sound Vessel Traffic Survey. The description of these sectors, and the various traffic assumptions utilized in determining encounter

rates within these sectors, are summarized in the following description.

Area 1: Eastern Strait of Juan de Fuca

The area begins approximately six miles east of Port Angeles, and encompasses the region east to the precautionary area surrounding buoy "SA," and north to buoy "RB," which denotes the entrance to Rosario Strait. Area 1 includes three traffic intersections, where vessels were assumed to be crossing other vessels tracks at approximately right angles. Vessels were assumed to follow the VTS Traffic Separation Scheme, and proceed at their normal speed throughout the area, after having slowed to pick up or discharge a pilot at the precautionary area (Area 8) at Port Angeles.

Area 2: Admiralty Inlet

This area encompasses Admiralty Inlet south and west of the precautionary area surrounding buoy "SA," to a line between Point No Point and the southern end of Whidbey Island. This area includes intersection traffic bound to and from Port Townsend and Hood Canal, (a total of 307 vessels) as determined from the Coast Guard Traffic Survey, as well as one ferry crossing.

Area 3: Puget Sound

This area includes Puget Sound south of Area 2 to a line between West Point and Skiff Point on Bainbridge Island. Area 3 includes intersection traffic bound from and to

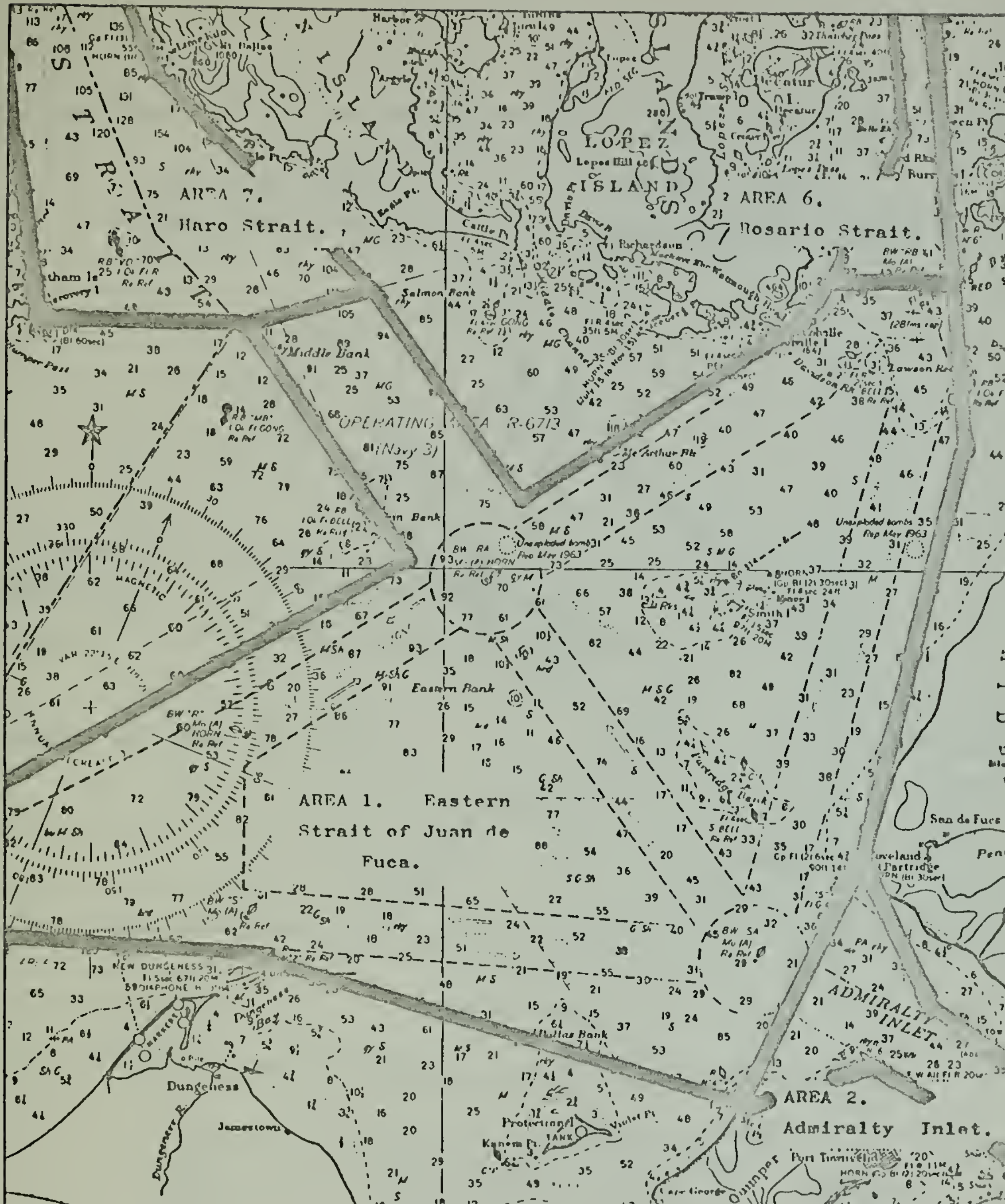

Figure 6-1

Vessel Traffic Lanes Within Area 1

Source: Strait of Georgia and
Strait of Juan De Fuca,
Chart C & GS 6300.

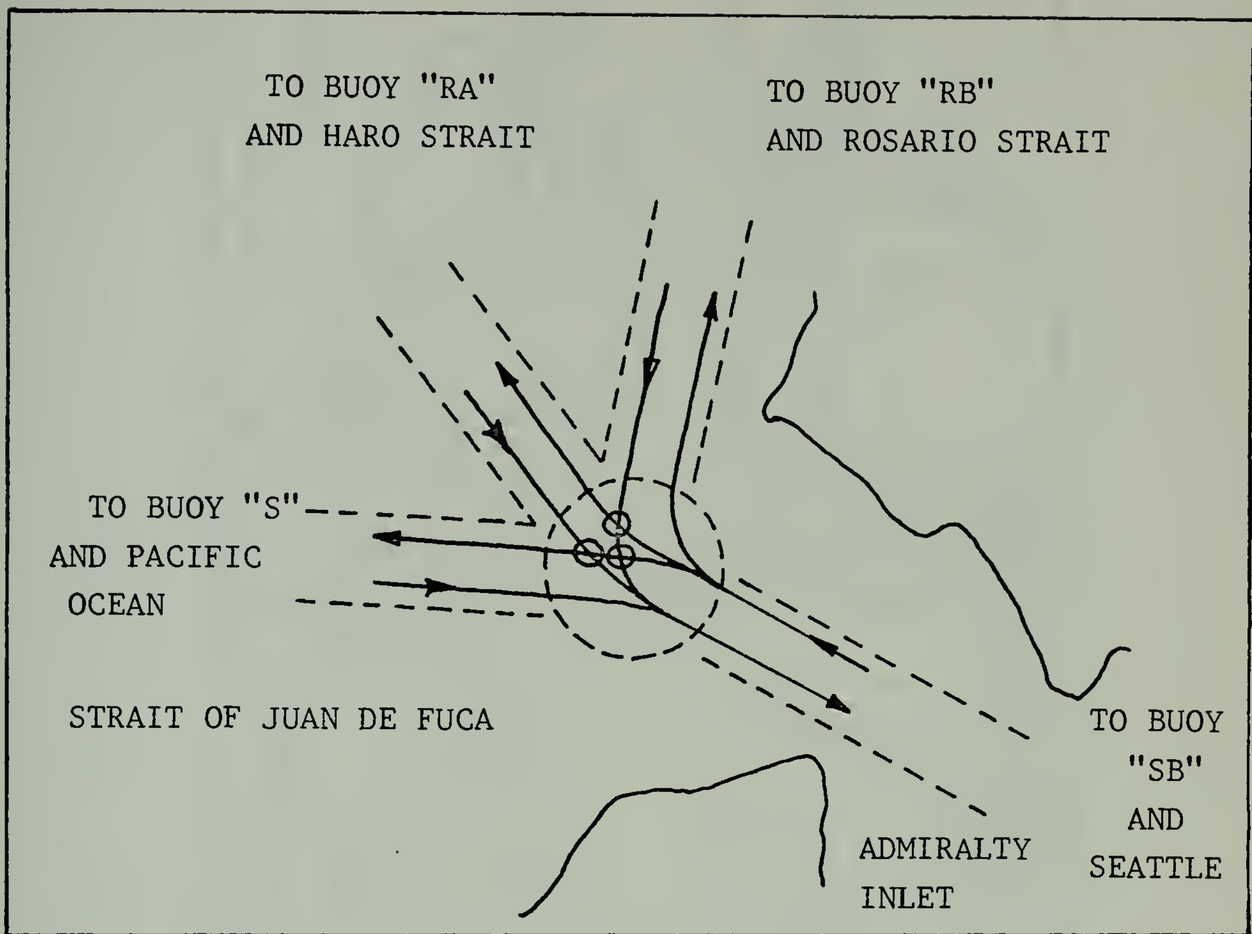

Figure 6-2

Encounters Within a Traffic Intersection

Estimated freighter crossing encounter situations within the traffic intersection at the entrance to Admiralty Inlet. Encounters were estimated for all conflicting traffic situations in a similar manner between all classes of vessels.

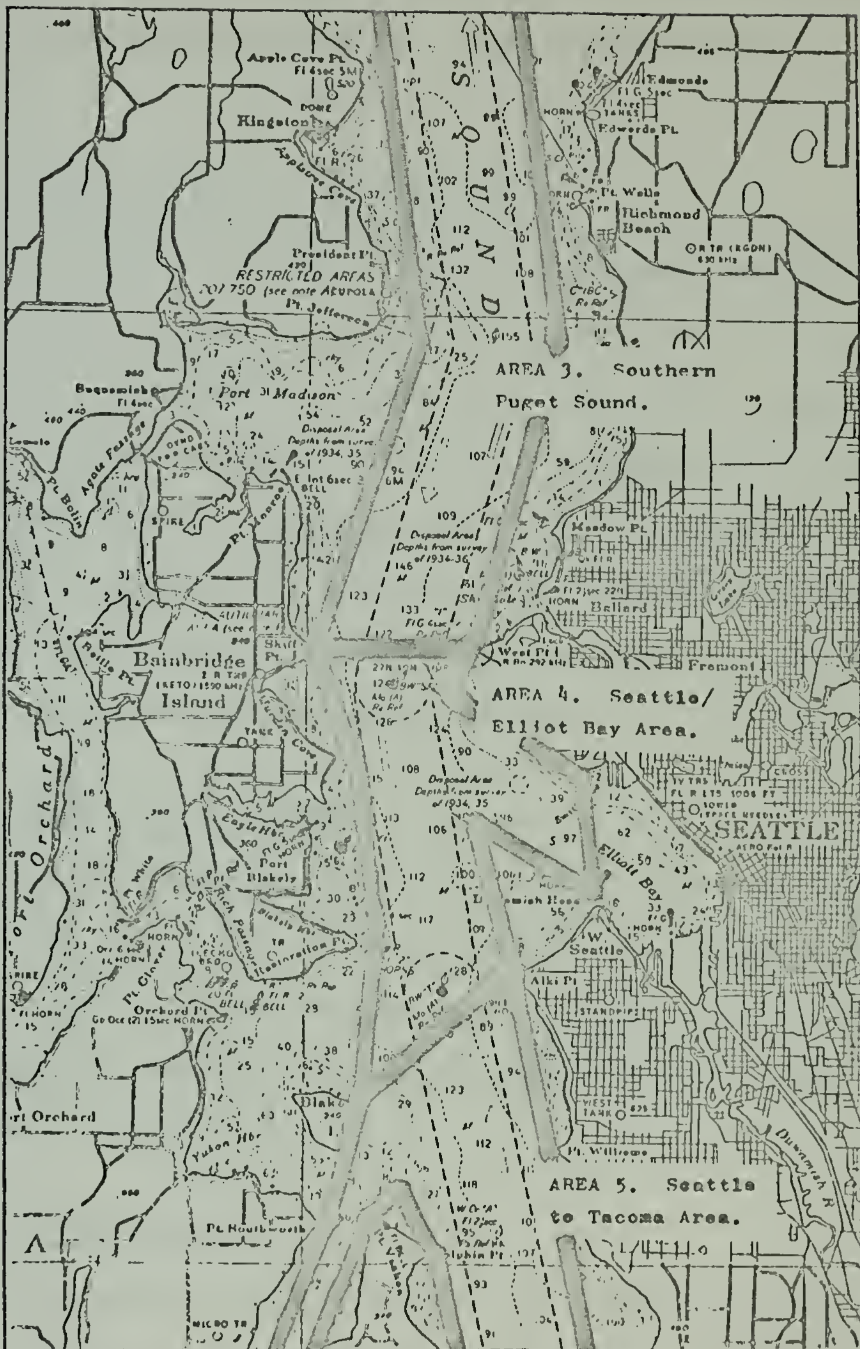

Figure 6-3

Vessel Traffic Lanes Within Lower Puget Sound

Source: Admiralty Inlet and Puget Sound, Chart C & GS 6401.

Possession Sound, Port Madison, Richmond Beach, Edmonds, and Shilshole Bay (a total of 587 vessels), as well as one ferry route.

Area 4: Seattle-Elliot Bay Approach

This area includes Puget Sound south of West Point and north of Alki Point, as well as a four square mile approach area east of the traffic lanes to Elliot Bay. Deep-draft vessels proceeding within this approach area to Elliot Bay were assumed to be moving at one half their normal speed. Area 4 includes traffic bound to and from Seattle and Bremerton (a total of 947 vessels), as well as two ferry routes which cross the traffic lanes.

Area 5: Seattle to Tacoma

This area consists of the region south of a line between Alki Point and Blake Island, to the approaches to Tacoma. There are two regularly traveled routes, through Colvos Passage and East Passage around Vashon Island, with one ferry route crossing the lanes.

Area 6: Rosario Strait

This area consists of Rosario Strait, north of Area 1 and buoy "RB," and includes traffic bound to and from Anacortes, Bellingham, and Cherry Point, as well as Canadian-bound vessels which depart from the existing traffic lanes at Alden Bank. Rosario Strait is limited in width, and consists of a single two-direction traffic lane south of Lummi Island. Traffic bound to and from Cherry Point, Bellingham Bay, and

Anacortes totalled 261 vessels, with 280 vessels departing or entering the traffic system at Alden Bank. Vessels were assumed to proceed at their normal speed, and to be uniformly distributed over the average effective width of a single two-directional traffic lane, which averaged approximately (.75) miles in width.

Area 7: Haro Strait

This area consists of Haro Strait, and is divided by the United States-Canadian border. At the present time, this area is not within the Puget Sound Vessel Traffic System. Projected plans for the entire region consist of a joint traffic management system to encompass all United States and Canadian traffic. Under this long-range plan, the Canadian government will manage vessel traffic within Haro Strait on both sides of the United States-Canadian boundary, and the United States Coast Guard will manage all traffic within the Strait of Juan de Fuca. Reporting requirements and procedures will be identical, and both the United States and Canadian systems will be compatible and complimentary.

There are no accurate figures available on traffic volume within Haro Strait. Based on estimates provided by the Canadian Ministry of Transport regarding traffic through the Strait of Juan de Fuca, the Haro Strait traffic was estimated to total 450 vessels per month. It was further assumed that the mix of vessel types, and their general characteristics were identical to those of United States traffic through the Strait of Juan de Fuca. This traffic volume of 250 freighters,

50 tankers, and 150 towing boats was assumed to be uniformly distributed over an effective traffic lane width of 1.5 miles, and proceeding at average transit speed.

Area 8: North of Port Angeles

This sector comprises the precautionary area to the north of Port Angeles. Deep-draft vessels proceeding between the Pacific Ocean and the various ports within the Puget Sound region are required to pick up and discharge a licensed pilot in this area immediately north of Port Angeles (Ediz Hook). It was therefore assumed that deep-draft vessels transitting this area were proceeding at half their normal speed throughout the length of this area. Area 8 serves as a link between the projected one-way traffic lanes which will be established within the Strait of Juan de Fuca, and the existing Traffic Separation Scheme which begins in Area 1. Area 8 is approximately 19 miles long and three miles wide, and traffic within this area was assumed to be uniformly distributed across an effective width of three miles, and proceeding both east- and west-bound. Deep-draft vessels (freighters and tankers) were assumed to proceed at one half their average speed, while towing boats were assumed to proceed at their average speed of 7.2 knots.

Area 9: Western Strait of Juan de Fuca

This area consists of two one-directional lanes, which begin north and west of Cape Flattery, in the Pacific Ocean, and continue through the Strait of Juan de Fuca to a

precautionary area north of Crescent Bay. These one-way lanes are expected to be established under a joint United States-Canadian traffic management system in the near future. The west-bound lane will be north of the United States-Canadian boundary, and the east-bound lane will be entirely in United States waters. The lanes will be separated by from two to three and one-half miles.

Encounter rates within Area 9 were estimated by assuming all traffic was proceeding in the general vicinity of these lanes, and uniformly distributed over an effective width of two miles. In fact, traffic through this area does not at present follow this proposed lane system. Vessels transitting this region normally follow a track so as to proceed in the shortest distance to their destination. This fact in the past has caused congestion in the vicinity of Cape Flattery, as vessels encounter opposing traffic concentrated in a relatively small area. The proposed lanes are therefore designed to eliminate encounters close to shore, and spread these potential encounters over a large open area of the sea, thereby eliminating blind encounters caused by vessels turning into traffic hidden by Cape Flattery.

As previously discussed in Area 7 (Haro Strait), the volume of Canadian traffic through the Strait of Juan de Fuca was estimated by the Canadian Ministry of Transport to approximately equal United States-bound traffic. For encounter-rate modelling, it was assumed that United States and Canadian

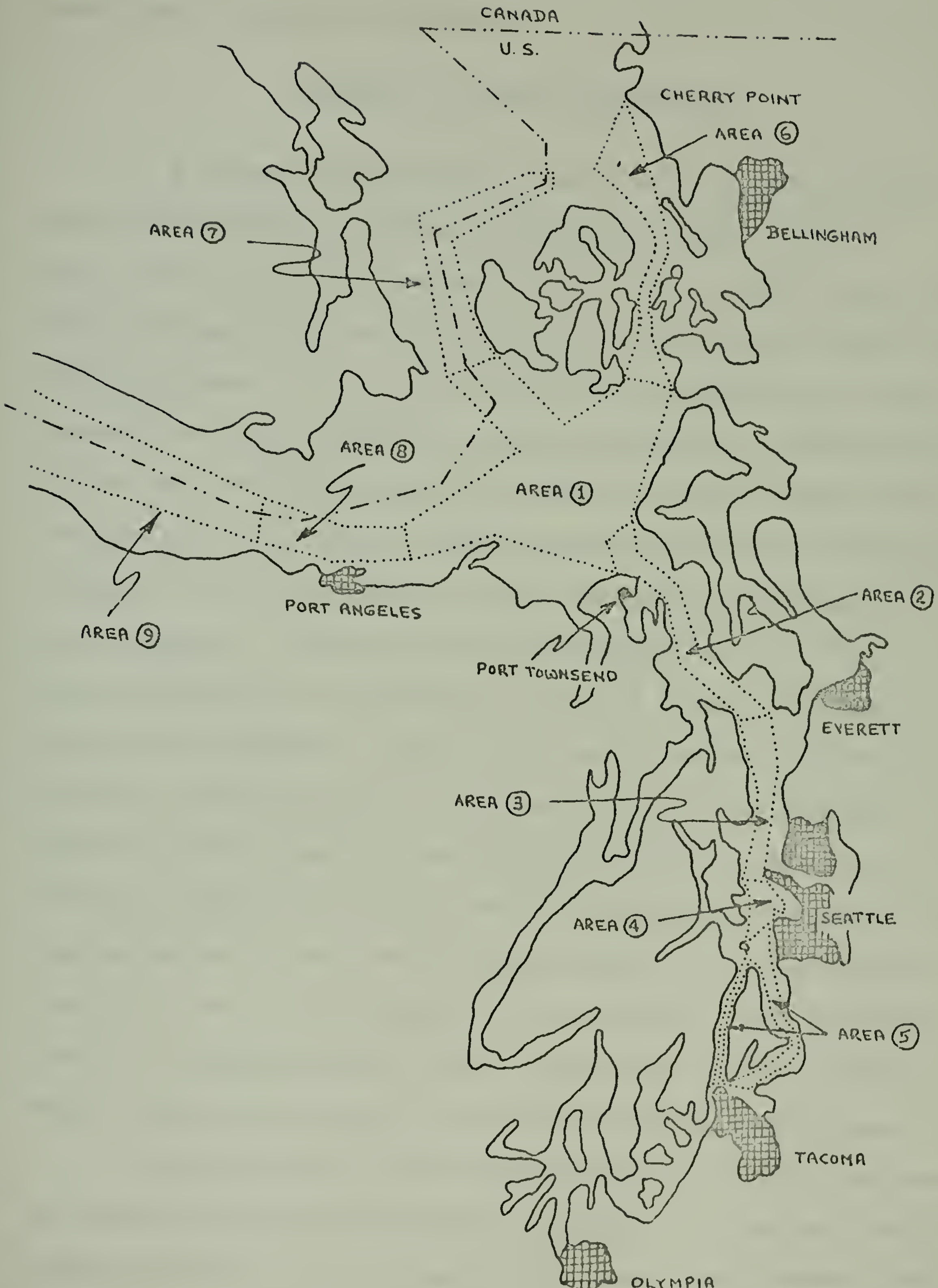

Figure 6-4

The Nine Encounter Areas of the Puget Sound Region

traffic were equal in all respects, including average size, speed, and density distribution.

SUMMARY OF VESSEL ENCOUNTERS

A summary of the total number of estimated vessel encounters within the nine geographical areas of the Puget Sound region is present below. It is again noted that these encounters do not represent all the traffic within the various areas. At the time this data was gathered, it was assumed that this traffic volume represented a large percentage of the ship and barge traffic within the Puget Sound region. Certainly as the Vessel Traffic Management System develops and evolves, it will include an ever-increasing percentage of the total traffic. Revised Rules and Regulations which will become effective in September 1974 will broaden the scope of vessel participation. These rules will further define the existing traffic lanes as a fairway, which will restrict the right of other vessels (particularly fishing vessels) to obstruct traffic within the Traffic Separation Scheme.[1] The incorporation of the revised Rules, and the establishing of traffic lanes in the Strait of Juan de Fuca, will therefore create a situation which closely approximates the conditions which this study assumed to exist for modelling purposes.

The sum of all projected encounters in the nine areas was found to be 2114 encounters per month. Based on traffic volume statistics determined by the Coast Guard Vessel Traffic

Survey, the number of encounters between the various classes of vessels is presented in Table 6-1.

Table 6-1

Total Encounters Per Month, E_{jk}, Within the Nine Sectors of Puget Sound. Total Encounters Per Month for April 1974 Between the Various Classes of Vessels, and the Percentage of Total Monthly Encounters In Parentheses

Vessel Class k	Vessel Class j				
	Freighters	Tankers	Tow Boats	Miscel-laneous	Ferry
Freighters	76 (3.6%)	44 (2.1%)	598 (28.5%)	24 (1.1%)	118 (5.6%)
Tankers		6 (0.3%)	140 (6.7%)	3 (0.1%)	17 (0.8%)
Tow Boats			558 (26.6%)	64 (3.1%)	425 (20.3%)
Miscellaneous				2 (0.1%)	19 (0.9%)
Ferry					2 (0.1%)

Table 6-2

Composite Encounters Per Month by Area (Estimated Encounters for April 1974 Within the Nine Areas of Puget Sound)

COMPOSITE ENCOUNTERS PER MONTH (APRIL 1974)

AREA 1.	(Eastern Strait of Juan de Fuca)		
	Traffic Lanes (5)	86	
	Intersections (3)	11	
	Total Encounters		97
AREA 2.	(Admiralty Inlet)		
	Traffic Lanes	381	
	Intersections at Port Townsend and Hood Canal	23	
	Ferry Crossings (1)	50	
	Total Encounters		454
AREA 3.	(Puget Sound)		
	Traffic Lanes	277	
	Intersections at Possession Sound, Port Madison, Richmond Beach, Edmonds, Shilshole Bay	26	
	Ferry Crossings (1)	119	
	Total Encounters		422
AREA 4.	(Seattle-Elliot Bay Approach)		
	Traffic Lanes	16	
	Intersections	24	
	Within Elliot Bay	324	
	Ferry Crossings (2)	105	
	Total Encounters		468

Table 6-2 (Continued)

AREA 5. (Seattle to Tacoma)		
Traffic Lanes		
East Passage	42	
Colvos Passage	22	
Ferry Crossings (1)	76	
Total Encounters		139
AREA 6. (Rosario Strait)		
Traffic Lanes		
Single	147	
Double	83	
Total Encounters		230
AREA 7. (Haro Strait)		
Traffic Lanes	101	
Total Encounters		101
AREA 8. (North of Port Angeles)		
Precautionary Areas	82	
Total Encounters		82
AREA 9. (Western Strait of Juan de Fuca)		
Traffic Lanes	121	
Total Encounters		121
Total Encounters in all Areas for April 1974		2,114

ANNUAL COLLISION RATE IN PUGET SOUND

The assumptions utilized in modelling encounter rates produces an estimated 2,100 encounters for the month of April 1974. The conditions which produced this estimate were assumed to be valid throughout the Puget Sound region, specifically, that vessels generally followed the prescribed Traffic Separation Scheme, and that vessels within this system did not encounter other types of vessels which were non-users of the system. In fact, a large number of vessel encounters may exist between user-vessels and fishing boats and pleasure craft. Periodic reports of large concentrations of fishing boats within the traffic lanes have been made to the Coast Guard Vessel Traffic System by deep draft vessels.[2] A further condition which tends to lower the encounter rate is the assumption that vessels transitted the proposed traffic lanes in the Strait of Juan de Fuca, thereby eliminating head-on encounters in this area. If these actual conditions could be realistically estimated, the overall encounter rate would be increased substantially in this region. A further increase would also occur with the inclusion of those vessels which were not system participants, but did enter or cross the traffic lanes.

Based on the conditions and assumptions which were used in the encounter rate model, a total of 25,000 encounters per year may be a reasonable estimate for the Puget Sound region (as defined by the nine traffic sectors). The only criteria available to judge the accuracy of this estimate is by

comparison with individual vessel transit data maintained in the files of the Puget Sound Vessel Traffic Center. A search of the vessel transit records for the week of April 14-20, 1974, produced 1,304 total "encounters" between vessels. The criteria by which an encounter was denoted differs significantly from that in the previously-developed encounter rate model. The Puget Sound Vessel Traffic Center informs all vessels transitting the system of the name and location of any vessel in its near vicinity, based on the information presented by a manually-operated plotting display. The criteria is quite broad, in that vessels are notified of the presence of other vessels within a radius of approximately seven to ten miles, whether in the same lane or on the opposite side of the precautionary area. By reducing the 1,304 encounters by two-thirds, to eliminate encounters with vessels in the opposite lanes, this produces an annual encounter rate of approximately 23,000. This figure does not include encounters within Haro Strait or the western portion of the Strait of Juan de Fuca. Nevertheless, the comparison denotes some reasonable correlation with the 25,000 encounters estimated using the encounter rate model.

It was previously stated that studies conducted by Fujii and Shiobara led to their conclusion that one in 100,000 vessel encounters may result in a collision. If this estimate can be applied to the annual encounter rate within the Puget Sound region, one may expect a collision rate on the order of one collision each four years. Again it should be

noted that the encounter rate was estimated for traffic adhering to a Traffic Separation Scheme within all of the nine areas of Puget Sound. Historical trends in vessel accidents have shown a frequency of occurrence of three collisions in four years since 1950. This accident rate does not include collisions involving large vessels with fishing vessels or pleasure boats. It should also be noted that many collisions are often unreported, especially those among smaller vessels. These smaller vessels (i.e. tugs) usually move at slower speeds, have protective fenders to absorb shock, and usually suffer slight damage in collisions with similar vessels. The United States Coast Guard VTS Issue Study estimated that the number of unreported accidents involving two vessels is significant, and stated that actual accident statistics are weighted heavily in favor of larger vessels, which usually suffer more damage and are therefore more likely to report accidents.[3]

UTILIZATION OF ENCOUNTER RATE MODELLING IN VTS DEVELOPMENT

It was previously stated that the Puget Sound Vessel Traffic System is a system undergoing continual change and development. Projected changes include the incorporation of radar surveillance of vessel traffic. Plans call for the initial installation of four radars to monitor a portion of the Puget Sound traffic prior to 1976. Funding constraints and equipment limitations preclude radar coverage of the entire system. Four alternative areas were initially evaluated for site selection. The area to be covered by radar was selected

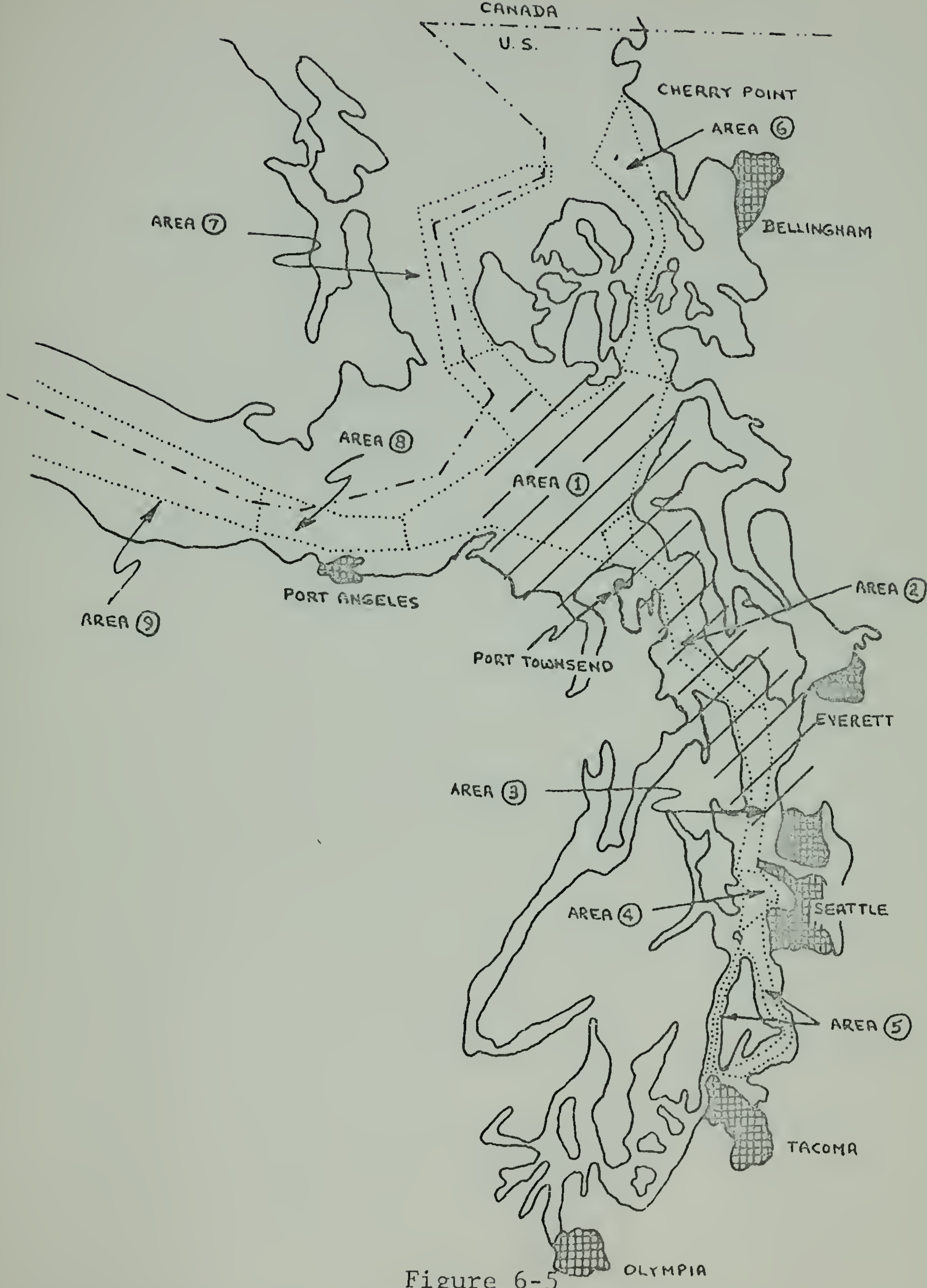

Figure 6-5

Puget Sound Vessel Traffic System Proposed Radar Coverage - Admiralty Inlet

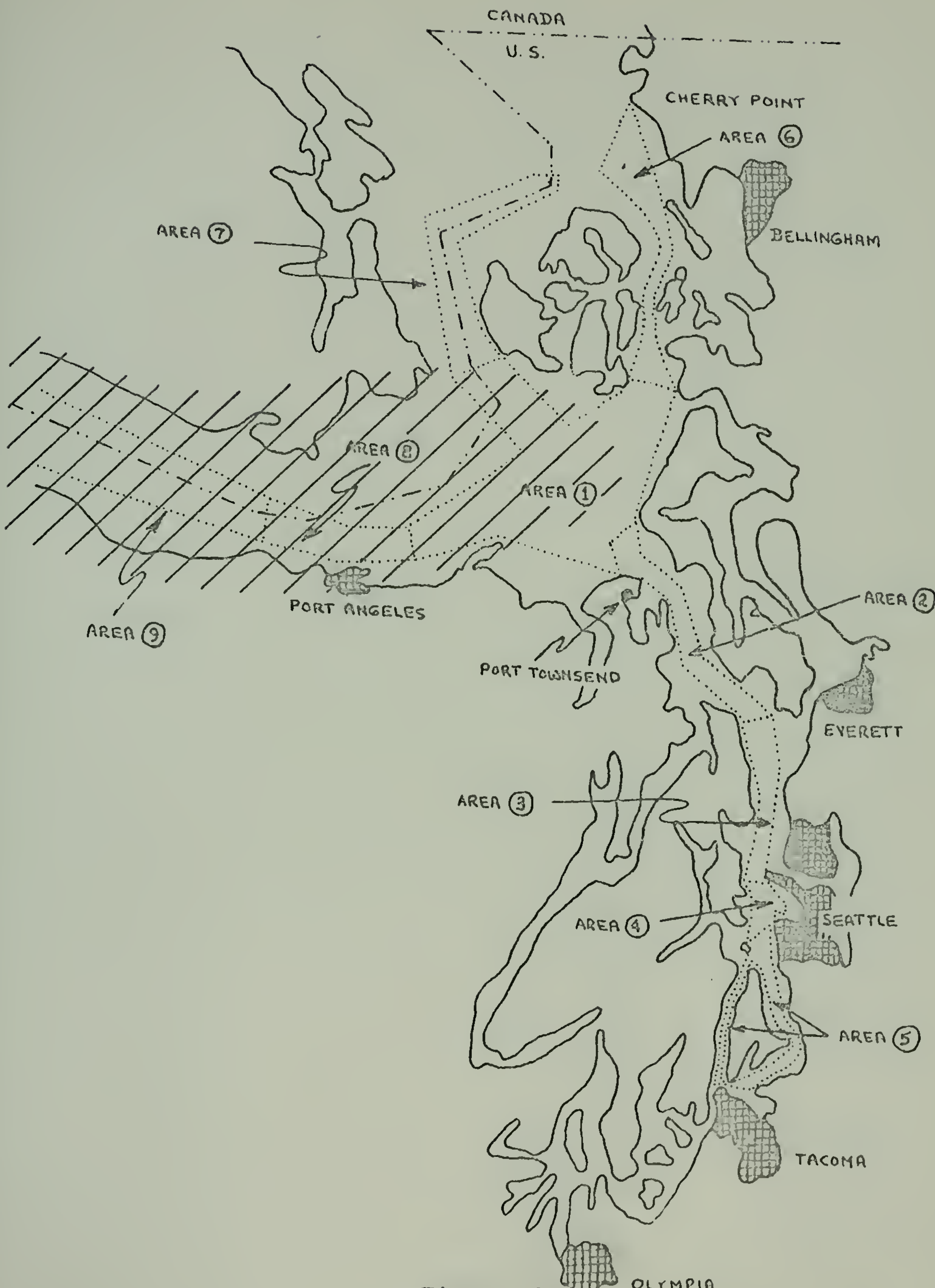

Figure 6-6

Puget Sound Vessel Traffic System Proposed Radar Coverage - Strait of Juan de Fuca

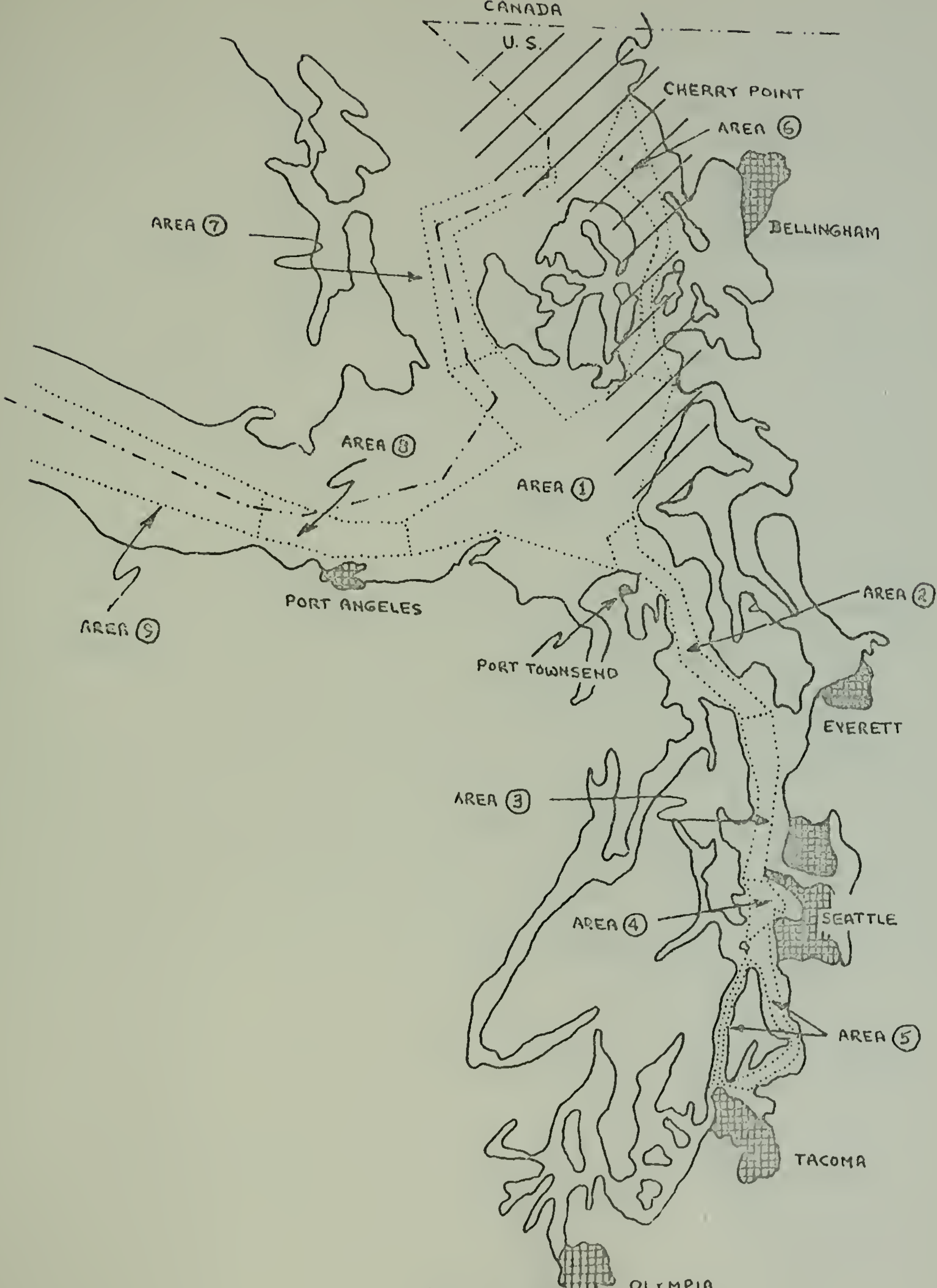

Figure 6-7

Puget Sound Vessel Traffic System Proposed Radar Coverage - Rosario Strait

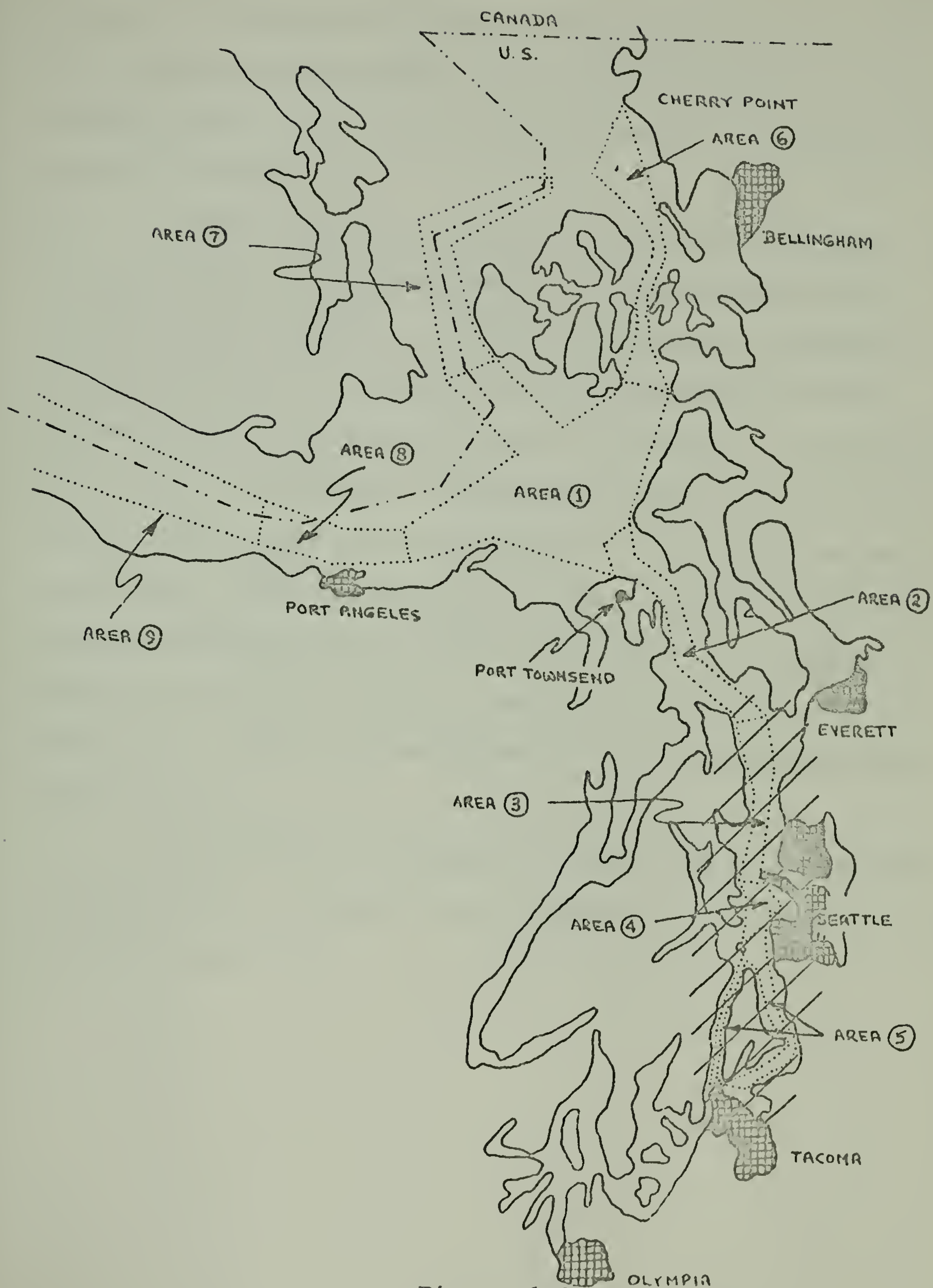

Figure 6-8

Puget Sound Vessel Traffic System Proposed Radar Coverage - Seattle to Tacoma

from the four feasible alternatives available: (1) Eastern portion of the Strait of Juan de Fuca and Admiralty Inlet, (2) Western three-fourths of the Strait of Juan de Fuca to the Pacific Ocean, (3) Rosario Strait, and (4) Puget Sound from Seattle to Tacoma.[4]

These four radar coverage alternatives (Figures 6-5 through 6-8) can be approximated by combinations of the encounter-rate sectors. A relative ranking of the radar coverage alternative can therefore be provided by using encounter rates within the areas as a criteria. Furthermore, the number of encounters involving various types of vessels within these areas can be estimated by use of the encounter rate model. This may provide a means to quantify the merits of one site selection over another, if there is a likelihood of higher encounter rates for a particular class of vessel or cargo (e.g. large bulk petroleum carriers, hazardous barge cargo, etc.).

The relative ranking of the four VTS radar coverage alternatives is estimated below, based on the number of vessel encounters per area.

Table 6-3

Relative Ranking of Radar Coverage Areas
Based on Estimated Encounter Rates

Radar Coverage Area	Encounter Rate Area	Estimated Encounter Per Month
(4) Seattle-Tacoma	Area 3, 4, 5.	1,025
(1) Admiralty Inlet	Part of Area 1, All of Area 2, Part of Area 3.	700-800
(3) Rosario Strait	Area 6, Part of Area 1.	250-300
(2) Strait of Juan de Fuca	Area 8, 9, and Part of Area 1.	250

CONCLUSIONS

It is recognized that the potential risk of a vessel collision is a function of several factors. Among those considered significant is the material condition of the vessel and its machinery and equipment, the competence and quality of the personnel who man it, and various factors which effect the encounter situation between two vessels. This encounter situation is dependent upon the relative closing velocity between vessels in potential conflict, the maneuverability and size of the vessels, and the transit rules under which the vessels are sailing. If one may define transit rules as having

the same connotation as flight rules, one may also believe that reducing the number of vessel encounters can be achieved in the same manner as reducing the number of near Mid-Air Collisions (NMAC), that is, by exercising some degree of control over the vessels. Recent legislation has created the authority to exercise some measure of control, and the technology to do so has existed for several years. While it is premature to suggest that a high degree of control is desirable or will be effective in all instances, nevertheless some degree of control may be necessary to reduce risks to an acceptable level. It is hoped that attempts to identify and reduce vessel encounters through traffic scheme revision or active methods of traffic management will lower the overall collision potential within Puget Sound. As more accurate data on vessel traffic movements becomes available, it is hoped that the encounter rate modelling technique presented in this study will provide a useful tool to evaluate the effects of changes in the Vessel Traffic System operating procedures.

FOOTNOTES

[1]"Vessel Traffic Systems, Puget Sound," Federal Register, July 10, 1974.

[2]Ibid.

[3]Vessel Traffic Systems Issue Study, Vol. 3, pp. 6-44-6-46.

[4]Operational Requirements for Puget Sound Vessel Traffic System, prepared by Chief, Marine Safety Division, Thirteenth Coast Guard District, p. 2.

BIBLIOGRAPHY

BIBLIOGRAPHY

Adlum, Merle, "Maritime Transportation Leg-Alaskan Responsibility to the Nation." Address to the Seattle Chamber of Commerce, May 20, 1974, Seattle, Washington.

Beattie, J. H., "Traffic Flow Measurements in the Dover Strait," The Journal of the Institute of Navigation, Volume 24, No. 3, July, 1971.

Fujii, Yahei, and Reijiro Shiobara, "The Analysis of Traffic Accidents," The Journal of the Institute, Volume 24, No. 4, October, 1971.

Fujii, Yahei, and Kenichi Tanaka, "Traffic Capacity," The Journal of the Institute of Navigation, Volume 24, No. 4, October, 1971.

Haight, Frank A. Mathematical Theories of Traffic Flow. New York: Academic Press, 1963.

Honeywell Marine Systems Center, A Proposed Automated Marine Traffic Advisory System for Puget Sound, Document 2330, July 29, 1971.

Jane's Fighting Ships 1969-70, Raymond V. B. Blackman, ed., Sampson Low, Marston & Co., Ltd., London, 1969.

Lloyd's Register of Shipping 1973-1974, Lloyd's Register of Shipping Trust Corp. Ltd. (London, 1973).

May, G. T. A., "A Method for Predicting the Number of Near Mid-air Collisions in a defined Airspace," The Journal of the Institute of Navigation, Volume 24, No. 2, April, 1971.

Neville, Adam M., and John B. Kennedy. Basic Statistical Methods for Engineers and Scientists. Scranton, Pa.: International Textbook Company, 1962.

Oceanographic Institute of Washington, Risk Analysis of the Oil Transportation System, a report to the 43rd Legislature, State of Washington.

Oudet, L, "How to Prevent Collisions," The Journal of the Institute of Navigation, Volume 24, No. 2, April, 1971.

"Ports and Waterways Safety Act of 1972," Public Law 92-340, 92nd Congress, H.R. 8140, July 10, 1972.

"Puget Sound Vessel Traffic System, Notice of Proposed Rulemaking," Federal Register, Volume 38, No. 150, Monday, August 6, 1973.

Richey, M. W., "Traffic Separation in the Dover Strait, A Report," The Journal of the Institute of Navigation, Volume 24, No. 2, April, 1971.

Royal Institute of Naval Architects and the Royal Institute of Navigation, Marine Traffic Engineering. (London, 1973).

Scripture, F. R., "Marine Radar Collision Avoidance System Requirements," Navigation, Volume 13, No. 4, Winter 1966-1967.

Sperry Piedmont Company, Final Report Lookout Assist Device Feasibility Studies, Vol. I, Contract No. MA-3374, August, 1965.

Stratton, Andrew, "Navigation, Traffic, and the Community," The Journal of the Institute of Navigation, Volume 24, No. 1, January, 1971.

Toyada, Seiji, and Yahei Fujii, "Marine Traffic Engineering," The Journal of the Institute of Navigation, Volume 24, No. 1, January, 1971.

U.S. Army Corps of Engineers, Waterborne Commerce of the United States, Part 5, 1970.

U.S. Coast Guard, Operational Requirements for Puget Sound Vessel Traffic System, unpublished report prepared by Chief, Marine Safety Division, Thirteenth Coast Guard District, August 2, 1973.

U.S. Coast Guard, Proceedings of the National Security Industrial Association Symposium on Coast Guard Vessel Traffic Systems, Department of Transportation, Washington, D.C., May, 1973.

U.S. Coast Guard, Puget Sound Vessel Traffic System, Department of Transportation.

U.S. Coast Guard, Puget Sound Vessel Traffic System Operations Manual, Department of Transportation, September, 1972.

U.S. Coast Guard, Vessel Traffic Systems Analysis of Port Needs, Department of Transportation, August, 1973.

U.S. Coast Guard, Vessel Traffic Systems Issue Study, Volume 1-4, Department of Transportation, March, 1973.

U.S. Department of Commerce, Admiralty Inlet and Puget Sound, chart C & GS 6401.

U.S. Department of Commerce, Strait of Georgia and Strait of Juan de Fuca, chart C & GS 6300.

Vagners, Juris, and Paul Mar. Oil on Puget Sound. Seattle, Washington: University of Washington Press, 1972.

Van Hoof, J. F. D., "The Air Analogy at Sea," The Journal of the Institute of Navigation, Volume 24, No. 3, July, 1971.

"Vessel Bridge-to-Bridge Radiotelephone Act," Public Law 92-63, 92nd Congress, S. 699, August 4, 1971.

"Vessel Traffic Systems," Federal Register, Volume 39, No. 33, Wednesday, July 10, 1974.

Washington State Ferries, Ferry Schedule Late Winter-Spring 1974, Schedule No. 70.

Washington State Ferries, "Regular Vessel Allocations Fall-Winter-Spring Schedule," Traffic Department Bulletin, September 11, 1973.

Washington State Ferries, Washington State Ferries Fleet 1974.

Yamaguchi, Atsutoshi, and Shozo Sakaki, "Traffic Surveys in Japan," The Journal of the Institute of Navigation, Volume 24, No. 4, October, 1971.

Young, Hugh D. Statistical Treatment of Experimental Data. New York: McGraw Hill, 1962.

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